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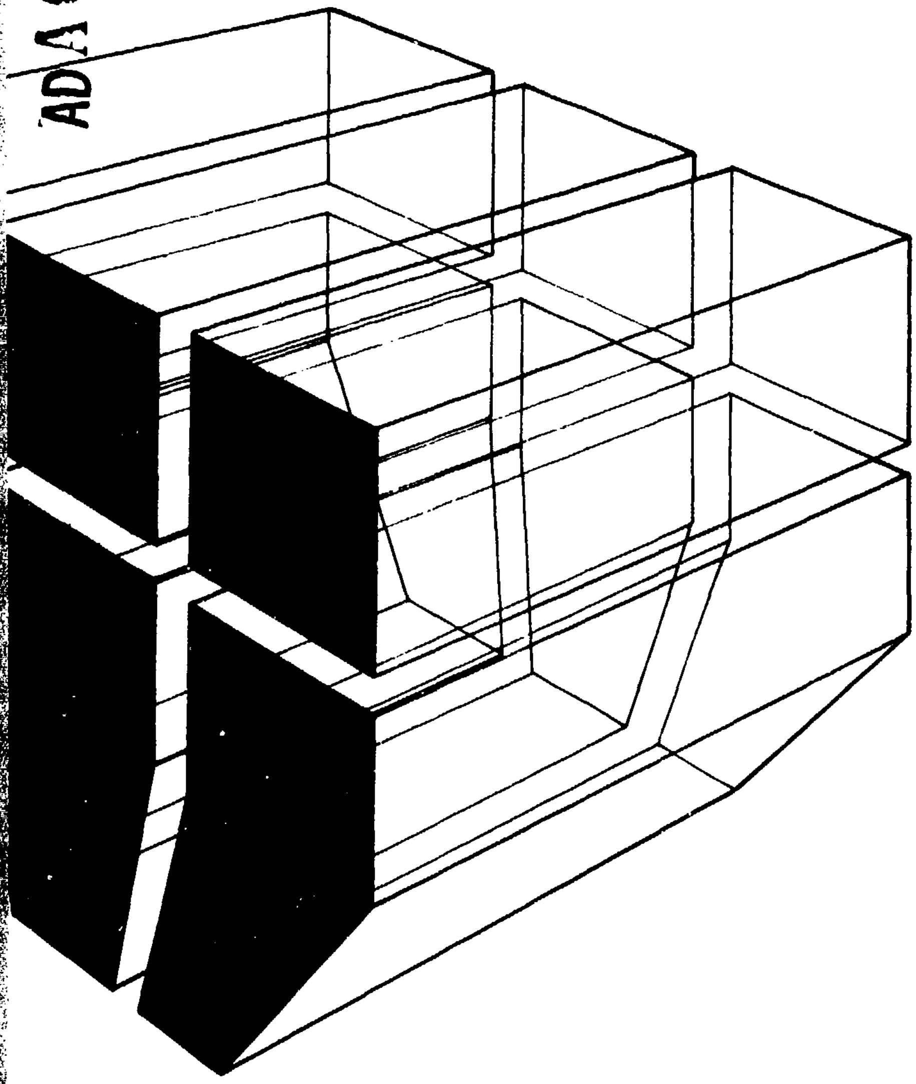
September 1976

INVESTIGATION OF GROUND FAULT CIRCUIT INTERRUPTER



by
W. D. Ford
R. G. McCormack

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The objective of this study was to ascertain the capabilities and limitations of the Ground Fault Circuit Interrupters (GFCI) used on Corps of Engineers (COE) supervised construction sites. Laboratory tests were conducted to determine (1) if GFCI samples from different manufacturers met the trip threshold design specifications of 5 mA + 1 and (2) if condensation, hot-cold environment, vibration, and RF, UHF, and microwave fields adversely affected their operation. A limited field survey of COE supervised construction sites was conducted to evaluate the actual

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application of the GFCI. This survey included trip threshold measurements and discussions with COE and contractor personnel after nuisance tripping had occurred.

The results of the laboratory and limited field study indicate that the present GFCI may be unreliable when used in a construction environment where there could be high condensation, RF, UHF, microwave, and switching noise fields. Nuisance trips (those trips which cause trouble, annoyance, or inconvenience not resulting from defective equipment) occurring in the field because of condensation, RF, UHF, microwave, and switching noise fields were veriified by laboratory tests in "worst-case" conditions. The condensation test, the RF, UHF, microwave test, and the switching noise test produced a large number of complete GFCI failures. (The overall failure rate was 24 percent--36 out of 138 tested.) Units tested were generally within the trip threshold values specified in Underwriters Laboratories Standard 943. High and low temperature environments have little effect on the operation of GFCIs.

While the GFCI is susceptible to some types of environmental degradation, continued use on construction sites is recommended. It is further recommended that the GFCI manufacturers improve their product's resistance to condensation and RF, UHF, and microwave energy.

END ABSTRACT

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The objective of this study was to ascertain the capabilities and limitations of the Ground Fault Circuit Interrupters (GFCI) used on Corps of Engineers (COE) supervised construction sites. Laboratory tests were conducted to determine (1) if GFCI samples from different manufacturers met the trip threshold design specifications of 5 mA $\pm$ 1 and (2) if condensation, hot-cold environment, vibration, and RF, UHF, and microwave fields adversely affected their operation. A limited field survey of COE supervised construction sites was conducted to evaluate the actual application of the GFCI. This survey included trip threshold measurements and discussions with COE and contractor personnel after nuisance tripping had occurred.

The results of the laboratory and limited field study indicate that the present GFCI may be unreliable when used in a construction environment where there could be high condensation, RF, UHF, microwave, and switching noise fields. Nuisance trips (those trips which cause trouble, annoyance, or inconvenience not resulting from defective equipment) occurring in the field because of condensation, RF, UHF, microwave, and switching noise fields were verified by laboratory tests in "worst-case" conditions. The condensation test, the RF, UHF, microwave test, and the switching noise test produced a large number of complete GFCI failures. (The overall failure rate was 24 percent--36 out of 138 tested.) Units tested were generally within the trip threshold values specified in Underwriters Laboratories Standard 943. High and low temperature environments have little effect on the operation of GFCIs.

While the GFCI is susceptible to some types of environmental degradation, continued use on construction sites is recommended. It is further recommended that the GFCI manufacturers improve their product's resistance to condensation and RF, UHF, and microwave energy.

FOREWORD

This research was conducted for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), and was jointly funded by Project 4A762719AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Task T1, "Development of Automated Processing for Military Construction and Facilities Engineering"; Work Unit 018, "Investigation of Ground Fault Circuit Interrupters"; and a reimbursable work order MCC-E-76-6 received from OCE. The study was conducted by the Electrical-Mechanical Branch (EPM), Energy and Power Division (EP), Construction Engineering Research Laboratory (CERL), Champaign, IL. The OCE Technical Monitor for this study was Mr. F. Knutkowski, and the CERL Principal Investigator was Mr. R. McCormack. Appreciation is expressed to Messrs. R. Neathammer, D. Hannum, and S. C. Hsu for their contributions.

Mr. R. G. Donaghy is Acting Chief of EP, and Mr. M. J. Pollock is Chief of EPM. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Deputy Director.

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INVESTIGATION OF GROUND FAULT
CIRCUIT INTERRUPTER

1 INTRODUCTION

Background

"A ground fault circuit interrupter (GFCI) is a device whose function is to interrupt the electrical circuit to the load when a fault current to ground exceeds some predetermined value that is less than that required to operate the overcurrent protection device of the supply circuit." This definition first appeared in the 1958 National Electric Code (NEC) and was one of two specific methods suggested to protect against shock hazards caused by underwater lighting fixtures used in swimming pools. Figure 1 is a block diagram of a typical GFCI.

The purpose of the GFCI is to protect persons from serious or fatal shock by limiting the time duration of the shock. (Available GFCIs reportedly operate within 1/40 of a sec). The GFCI is designed to trip below the "let-go" current threshold, which is defined as the maximum current at which a person is still capable of letting go of the source causing the shock by using muscles directly stimulated by the current. This value is approximately 9 mA for men and 6 mA for women.* Theoretically, serious damage or death will eventually occur if the individual is not freed from currents above his threshold of "let-go" current (see Figure 2).

It was soon recognized that a GFCI could provide protection in other areas. In 1971, the NEC required that GFCIs be installed to protect outdoor receptacle outlets, receptacle outlets close to swimming and wading pools, receptacle outlets on construction sites, and electrical equipment used with storable swimming pools. The 1975 NEC further increased the GFCI requirement to include bathroom receptacle outlets, circuits to underwater lighting fixtures, and branch circuits supplying fountain electrical equipment.

Of particular interest to the Corps of Engineers (COE) is NEC Article 210-7, 1975, which states that all 120-V, single-phase, 15- and 20-A receptacle outlets which are not a part of the permanent wiring of the building or structure shall have GFCIs for personnel protection.

The Underwriters Laboratory, Inc. Standard 943 (Standard for Ground Fault Circuit Interrupters) sets requirements for construction and

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* The values listed are minimums for a test group. The average values are 16 mA for men and 10.5 mA for women as reported in C. F. Dalziel, *Ground Fault Circuit Interrupter*, paper presented to Safety and Health Advisory Committee, U.S. Department of Labor, WASH, DC (November 7, 1973).

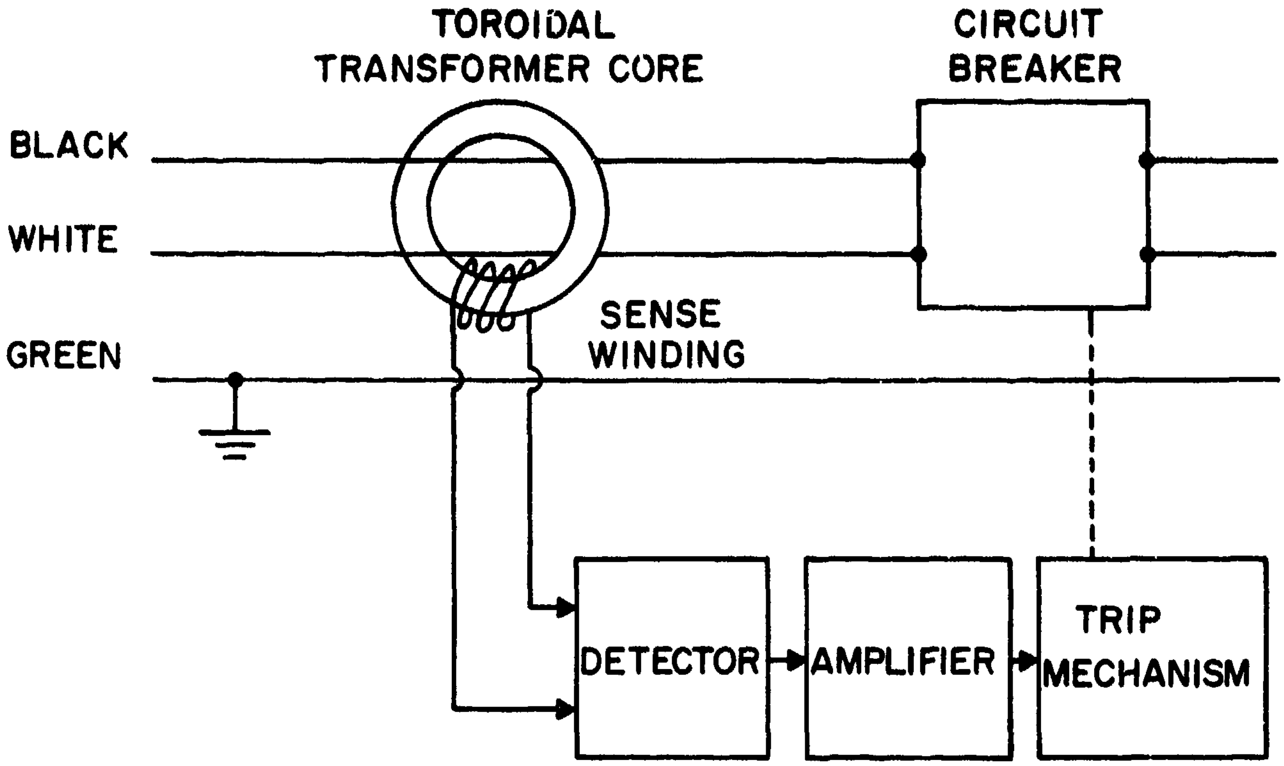
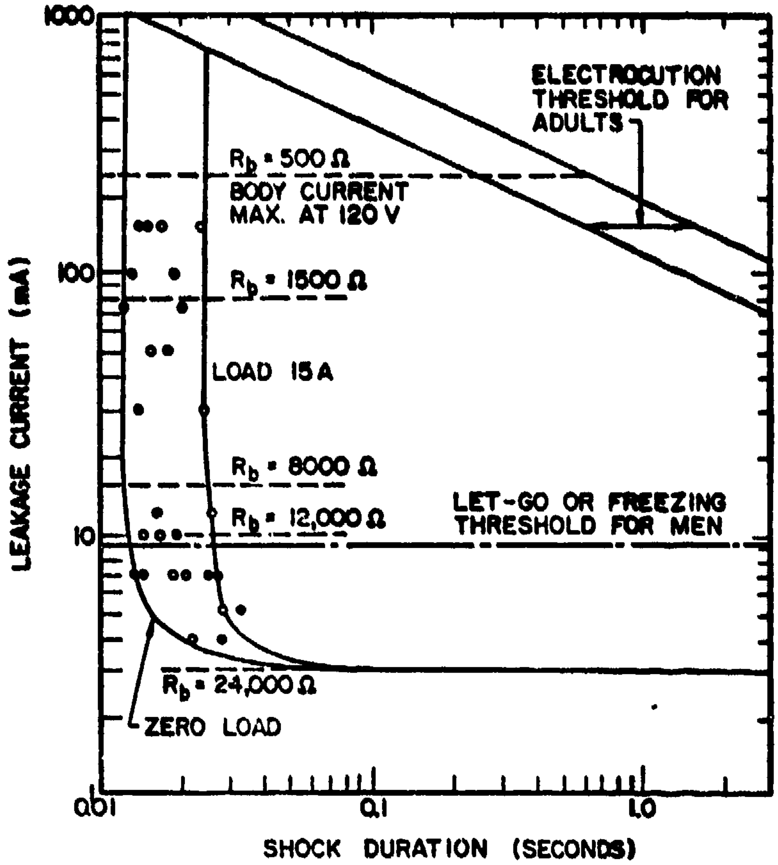


Figure 1. Block diagram of typical GFCI.



Relationship between trip current and shock duration for a typical Rucker GFI. The electrocution threshold and the let-go (freezing) threshold for adults is included to give proper perspective. The horizontal dashed lines indicate body current for variously assumed body-circuit resistances. It is generally accepted that the minimum likely body resistance in low-voltage accidents for a current pathway between major extremities with liquid contacts is 500, and for the perspiring hands of a technician, 1500 ohms. Corresponding resistances for dry hands or casual contacts are too variable to mention precise figures. Note that the current-time curves rise almost vertically for currents in excess of twice the trip value.

Figure 2. Relationship between trip current, shock duration, and effect. (From Charles F. Dalziel, "Transistorized Ground-Fault Interrupter Reduces Shock." *IEE Spectrum* [January 1970]).

performance of the GFCI. The devices are designated as Class A--Group 1, which are designed to open when the current leakage to ground reaches 5 $\pm$ 1 mA; and Class B, which are designed to open when the leakage to ground reaches 20 mA. Underwriters Laboratory, Inc. (UL) has designated that Class A devices be used on all new installations. The Class B GFCIs were developed for use with underwater lighting fixtures in existing swimming pools. UL is now proposing to withdraw listing of the Class B GFCI.

In compliance with the National Electric Code and Underwriters Laboratory, Inc., the Corps of Engineers--as responsible agency for both Army and Air Force construction--is presently requiring the 5 $\pm$ 1 mA GFCI to be used on the construction sites it supervises through the requirement for conformance to the NEC.

The Associated General Contractors of America (AGC) has strongly opposed incorporation of GFCI requirement revisions into Corps of Engineers' general safety requirements, noting "that the use of GFCI is an unproved technique which is causing them considerable difficulty and that such use should be suspended until improvements are made."[1] However, the policy of the Corps at this time is to continue to prescribe its use based on the conclusion, "that even with present difficulties it does provide the promise of saving lives."[2] The prescription has the provision that the contracting officer has the authority to waive its use "if we find that the use of GFCI is inhibiting the prosecution of work by an unacceptable degree of nuisance tripping."[3]

The Corps position is to attempt to foster the continuing development of GFCIs. An initial step to this end was the undertaking of a technical evaluation of GFCIs to ascertain their capabilities and limitations and to determine what their operating parameters should be.

Purpose

The purposes of this study were (1) to determine by field evaluation whether GFCIs were nuisance-tripping; (2) to ascertain in the laboratory the GFCI's capabilities and limitations through testing for trip threshold, RF, UHF, microwave field exposure, hot/cold environment, and under high condensation conditions; (3) to evaluate the causes for nuisance trips; (4) if applicable, to recommend changes in standards for GFCIs

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[1] Letter from LT GEN W. C. Gribble, Jr., U.S. Army Chief of Engineers to BRIG GEN Charles O. McGinnis, Division Engineer, Southwestern; subject: Use of Ground Fault Circuit Interrupters (2 July 1975), p 1.

[2] Gribble letter, p 2.

[3] Gribble letter, p 2.

used on Corps of Engineers supervised construction sites, and (5) to recommend changes in the design parameters of the GFCI.

Approach

Personnel from Corps of Engineers Districts and Divisions, AGC members, and other organizations performing related work were contacted to define GFCI problem areas. A conference was held at CERL with representatives from the OCE Research and Development Office, Safety Office, and Civil Works and Military Construction Directorates. The objective, approach, and scheduling of GFCI research were discussed and defined.

A detailed laboratory test plan (Appendix A) was prepared and sites selected for the survey were discussed with representatives from the Office of the Chief of Engineers. The field site survey was started, test samples available locally were procured, and those not locally available were ordered. A special CERL threshold tester was constructed and threshold determination tests were initiated.

Information obtained from the field survey was examined and analyzed, and the detailed test plan was modified accordingly; RF field exposure, UHF/microwave field exposure, switching noise, vibration, hot/cold exposure, and condensation tests were performed independently.

A meeting was held at CERL with National Electric Manufacturers Association (NEMA) GFCI personnel; representatives from most major manufacturers attended to insure that CERL tested the latest versions of their GFCIs, to review test plans, and to provide additional background information. Each manufacturer agreed to send CERL six of his company's latest models for testing, and each phase of testing was completed for all units except those that failed permanently during the tests.

2 DEVICE OPERATION

The GFCI consists of a toroidal differential sensing transformer that detects any current unbalance between the neutral and hot wires, and solid-state components that amplify the different currents to actuate a solenoid which trips open the circuit (see Figure 1). The device limits the time that a person might receive a shock if the current producing the shock is above the GFCI threshold trip value. Underwriters Laboratory, Inc. (UL) has specified that this trip value will be 5 ± 1 mA, which is below the "let-go" threshold defined in Chapter 1.

Unfortunately, electrical tools, extension cords, plugs, and connectors--and even the GFCI itself--possess inherent leakage characteristics which cannot be avoided. UL has standards for limiting the leakage of new tools and of the GFCI to 1/2 mA. There are older portable tools, however, that have as much as 5 mA leakage; calrod heaters and fluorescent lights are other examples of devices that have high leakage currents.

The main purpose of electrical power on construction sites is to operate tools during construction. These tools almost always must be interconnected to the power receptacle with either one or more extension cords. These cords, plugs, and receptacles are exposed to being run over, stepped on, dragged through water, rained on, pulled, jerked, and other unavoidable punishment. When the cords become battered, current leakage increases and may surpass the 5 ± 1 mA threshold trip value.

Corps safety personnel have stated that if leakage increases substantially, the cord or device is not safe and should be replaced. The contractor, who is accustomed t. using cords in seemingly worse condition (where not protected by GFCI) and who claims to have experienced no shock incidents, opposes having to replace these cords.

3 FIELD EVALUATION

Since the electrical system is more exposed to weather conditions at the beginning of a construction project, the frequency of nuisance tripping* had often changed between the time that a site contractor had reported problems and the time the CERL field investigation was made; therefore, much of the field information in this report is based on interviews with both the contractor and Corps of Engineers site personnel. The information is believed to be relatively factual. Field data were derived from:

1. Trip threshold measurements on GFCIs

2. Observations of trips caused by operation of electrical tools

3. Observations of trips caused by operation of radio transmitters.

4. Observations of installed GFCIs which had become inoperative due to failure.

All contractor comments considered in the evaluation were obtained in the presence of COE site personnel and were not contested.

Certain questions and answers that became apparent during the field site investigation must be considered before making a final decision about GFCIs. The following discussion of these questions is based on the field evaluation. A laboratory test program was designed to provide data input to help answer the questions (Chapter 4).

Q1. Were poor-quality GFCIs used at construction sites?

A. Contractor and COE personnel from five sites using GFCIs (50 percent of those studied) reported a large number of GFCI failures or low-threshold trip currents before or shortly after installation. Other sites did not possess the necessary testing equipment to enable these evaluations. Underwriters Laboratory, Inc. had at first specified that GFCIs should trip at a value of no more than 5 mA, leaving the lower limit open. The requirement was later changed to 5 mA $\pm$ 1 (UL Standard 943). A meeting with NEMA GFCI personnel revealed that characteristics of the latest GFCIs and those used in the field were definitely different.

Q2. Are the GFCI requirements logical?

A. From a contractor's viewpoint, not completely. For example, GFCI protection is required only on 120-Vac, 20-A circuits. Most construction sites also use 240 Vac, which is more hazardous than 120 Vac; GFCIs are not required for this voltage.

* Trips which cause trouble, annoyance, or inconvenience not resulting from defective equipment.

Dalziel[4] has conducted considerable research to determine "let-go" currents and electrocution thresholds. He has shown that allowable levels are a function of the size of the person. The current GFCI with a 5 ± 1 mA trip threshold is required by Underwriters Laboratories Inc. for providing protection in the home, where the person to be protected may be a small child or an elderly person. Thus, if 5 ± 1 mA provides adequate protection for the home, then a higher threshold may be adequate for the construction site where workers are predominantly adult males. Trip thresholds as high as 30 mA are standard in some foreign countries and have not been publicized as causing electrocutions. (See Appendix C, "Foreign Experience.")

The contractor feels that he is required to provide double protection, since a third-wire ground system and GFCIs are both required; either, when properly maintained, will protect the worker from shock by a completed path to ground. From the viewpoint of COE safety personnel, the condition of grounding systems cannot be assured, the condition of cords and tools is not always new, and operation may take place in a wet environment. Therefore, they feel further protection is essential, and added protection can be provided by a properly designed GFCI.

Q3. Were the required locations of GFCIs consistent?

A. No. For example, the contractor doing rehabilitation work at Fort Lewis, WA, was not required to use GFCIs, while contractors doing similar work at Lowry AFB were required to use them. At Lafayette field sites (New Orleans District), GFCIs were required on all circuits in temporary trailers, including baseboard heaters and lighting, while other Districts did not require any GFCI protection for temporary trailers. The NEC does not require baseboard heaters and lighting circuits to be protected by GFCIs, but various interpretations of the regulations have resulted in GFCI usage. (NOTE: The NEC allows receptacles connected to permanent wiring to be unprotected by GFCIs at COE sites. The Contracting Officer is allowed to determine GFCI usage, since he has jurisdiction over NEC regulations.)

Q4. Did Corps of Engineers personnel assist the contractor in solving his problems?

A. At some sites, fewer problems existed when knowledgeable Corps personnel were available to investigate the complaints and to show

[4] C. F. Dalziel, *Ground Fault Circuit Interrupter*, paper presented to Safety and Health Advisory Committee, U.S. Department of Labor, WASH, DC (November 7, 1973).

the contractors that a tool, electrical cord, or the GFCI itself was defective. (NOTE: Contractors accept responsibility for providing a knowledgeable specialist at the site.)

Appendix E summarizes the results of GFCI usage reported by contractors and COE personnel during 12 field site visits conducted between 14 October 1975 and 23 March 1976. An analysis of data in Appendix E yielded the following results:

Cause of GFCI Trip	Percent of Surveyed Sites Reporting Problem
Long Extension Cord	80
Moisture	70
Defective GFCIs	50
RFI, UHF, Microwave	30

In addition to CERL's field studies, OCE conducted a questionnaire survey of field GFCI usage at all CE construction sites. Survey results are reported in Appendix F.

4 LABORATORY TESTING

The UL 943 standard of 1974 and previous revisions denote a Class A GFCI as a device that will trip at 5 mA or more. This was revised to 6 mA or more as of January 5, 1976. UL did not specify a lower limit at which the GFCI should trip until the November 1975 UL 943 revision. Para 21.6C specified that under the most "adverse conditions," the Class A GFCI is not to trip at less than 4 mA when ambient air temperature is less than 5°C (23°F) or more than 40°C (104°F).

Threshold tests were performed for two reasons: (1) to ascertain the test sample GFCI's trip threshold as a standard for comparing the same GFCI in adverse environmental conditions and (2) to ascertain that the GFCI tested was typical of those used on construction sites.

The RF, UHF, microwave, switching noise, and field exposure tests were made because reports from construction sites indicated that these were problem areas.

Vibration tests were performed because GFCIs must be used on portable generators where they are subjected to vibrations from the driving source. These tests also ascertained the effect of possible vibrations common on permanent installations; i.e., ground transmission of vibration caused by operating equipment, such as trains or trucks, and the slamming of doors close to a GFCI.

Hot/cold tests were performed because a GFCI at a construction site is normally installed outside where it is subjected to temperature extremes.

The most serious problems reported at field sites were nuisance trips that were thought to be caused by moisture. The problem was usually attributed to external extension cords and tools used on the GFCI circuit. Some reports of condensation producing lower GFCI trip values were received; only three sites possessed the threshold trip current reading instruments. Condensation tests were conducted to observe the effect of moisture on the trip threshold.

(NOTE: The COE has about 300 active construction projects, but only 12 were visited. It is recognized that GFCI performance may vary with different site conditions. The information obtained, however, is believed to be typical of all sites).

GFCI Sample Description

Description of Operation

A GFCI senses the current flowing in the hot and neutral wires of an electrical circuit and detects any unbalance (difference) between

them. A completed circuit to an electrical load normally uses the hot and neutral wires, with equal but opposite currents flowing in each. A ground fault will drain current from the hot wire directly to the ground, causing an unbalance in the hot and neutral currents. This condition is detected by a specially designed transformer within the GFCI. Small signals from this transformer are amplified and applied to a trip coil driver controlled by output from a threshold sensing device. If the unbalance is above a predetermined threshold, the GFCI will trip and remove power from the circuit; thus, if the fault is caused by a person, he is saved from a long-duration shock.

GFCI Types Available

Four basic types of GFCIs are available for use on construction sites:

1. A circuit-breaker type for use in load center panels (Figure 3).

2. Receptacle types for use in standard receptacle boxes (Figure 4).

3. A portable type that uses one ground fault sensor for numerous circuits (Figure 5).

4. Load center panels with separate ground fault sensors (Figure 6).

GFCI Specifications

Specifications for manufacturing and testing GFCIs are summarized in UL Standard 943 of 1974.

Test Sample Acquisition

The first samples for the evaluation program were randomly selected from local distributors. The first group contained six circuit breaker samples from each of the following manufacturers: Square D, Zinsco, Cutler Hammer, General Electric, Bryant, and Federal Pacific Electric. In addition, six receptacle samples were ordered from each of the following: Pass and Seymour, 3M, and Leviton; a "Spider" type was obtained from Hubbell. All of the first samples were single-phase units with a 20-A trip rating.

When the samples were received, it was determined that all except the 3M receptacles were earlier models than those currently manufactured. It was then decided that each manufacturer would provide six of his latest samples for the test program (Table 1). All of the latest samples were single-phase, 20-A units.

Inquiries to manufacturers have indicated that it is difficult to identify exactly the latest model of the units used as test samples. Some manufacturers have changed a unit's design or a part of its design as many as five times. However, all manufacturers have had only one

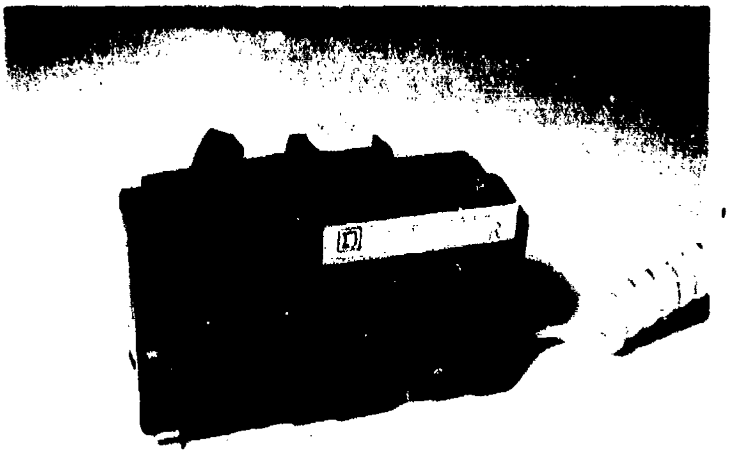

Figure 3. Load center circuit-breaker GFCI.

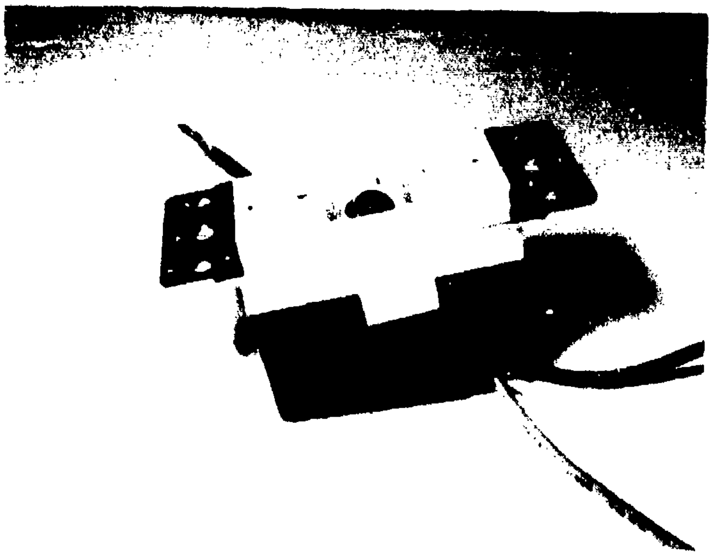

Figure 4. Receptacle type GFCI.

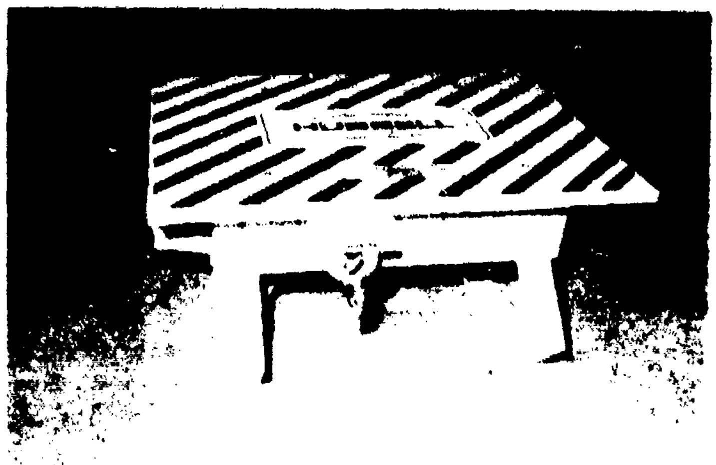

Figure 5. Portable GFCI load center (Hubbell "Spider").

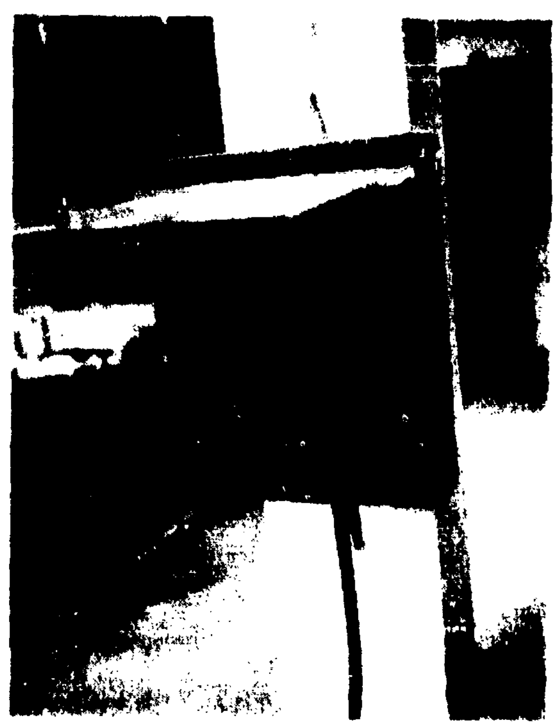

Figure 6. Load center panel with separate GFCI.

Table 1

Additional Samples Provided by Manufacturer

	Quantity and Date Received	
Manufacturer	Receptacle	Circuit Breaker
3-M	6 each, Jan 1976	
Pass & Seymour	6 each, Jan 1976	
Leviton	6 each, Jan 1976	
AMP Paragon	6 each, Jan 1976	
Square D	6 each, Feb 1976	6 each, Feb 1976
GE	6 each, Feb 1976	6 each, Feb 1976
American Switch (formerly Zinsco)		6 each, Feb 1976
ITE		6 each, Feb 1976
Cutler-Hammer		6 each, Feb 1976
Federal Pacific		6 each, Feb 1976
Hubbell		6 each, Feb 1976

NOTE: No additional Bryant units were needed, because the first ones received were of the latest design configuration.

design since the 5 $\pm$ 1 mA units were introduced. These units are identified by an "R" stamped or imprinted on the GFCI case. Thus, all CERL samples stamped with an "R" were the most recently designed units.

Instrumentation

Trip Threshold

The special requirement of measuring GFCI reaction time necessitated construction of a special threshold fault tester by CERL. Figure 7 illustrates the circuit description of this tester. Appendix B describes the tester.

Radio Frequency Interference (RFI) Testing

The instrumentation used for the RF field exposure tests is represented in block diagram form in Figure 8. (The ground fault tester, designed by CERL, was described earlier.) The signal source normally used was a Hewlett Packard 8601A Generator/Sweeper, which can provide either CW, AM, or a swept range of frequencies from 100 kHz to 110 MHz. An Electronic Navigation Industries Model 310L RF power amplifier was used to boost the power level to 10 W. This amplifier has a pass band response of 100 kHz to 110 MHz. Thus, changing frequency required only turning the dial of the signal source. For broad-band noise testing, a General Radio Noise Generator, Model 1390A, was substituted for the 8601A as a signal source. This generator provided noise with flat spectral density from 100 kHz to 5 MHz. Noise power level attainable was 20 W. (NOTE: RF power levels at a field site are unknown. UL is currently establishing a test to simulate field conditions.)

The RF field simulator used was a parallel plate transmission line with a flat center section and tapered end sections (Figure 9). The flat center section was 6 ft (1.8 m) long and 2 ft (0.6 m) wide. The flat plates were separated by a distance of 10 cm to enable simplified calculation of field intensity in volts per meter. The tapered sections on each end of the simulator allowed connection of source and load, while maintaining approximately the same characteristic impedance used for the flat center section. A Time Domain Reflectometer determined the characteristic impedance of the line, which was approximately 50 Ω.

UHF/Microwave Field Exposure

The instrumentation used was:

1. UHF

   Antenna - Dipole, 11-in. (27.5 cm)
   Source - General Radio Unit Oscillator Model 1208-A
   Power Monitor - Bird Model 43 Thruline Wattmeter

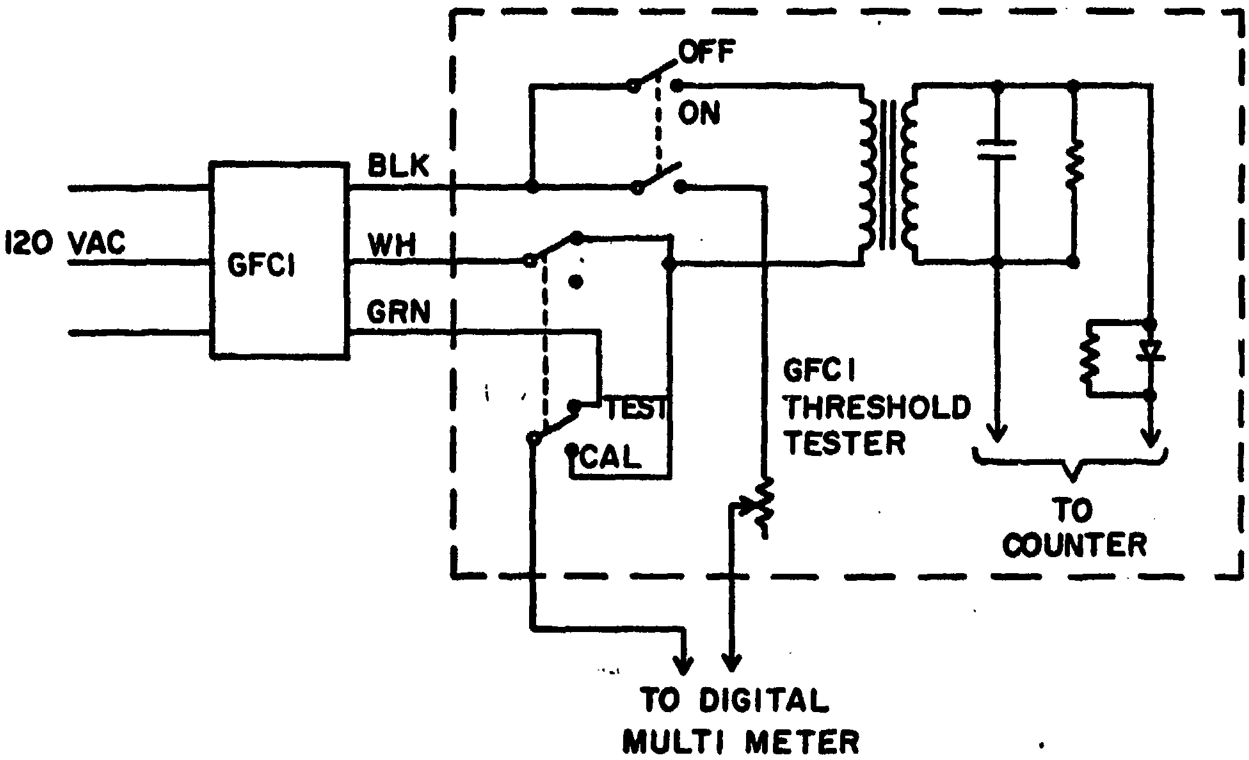

Figure 7. CERL threshold fault tester.

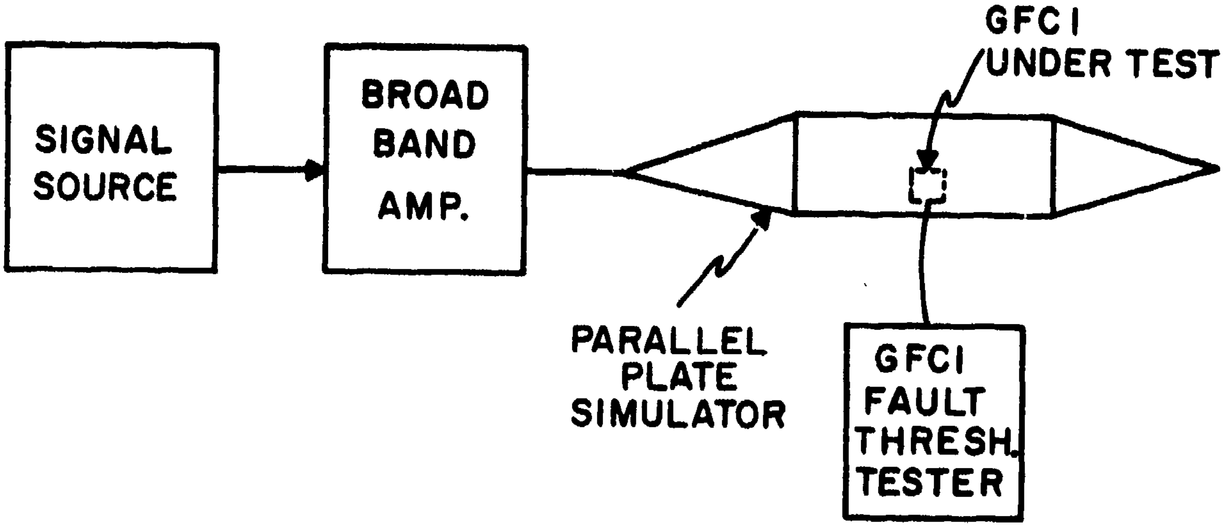

Figure 8. Block diagram, RF field exposure instrumentation.

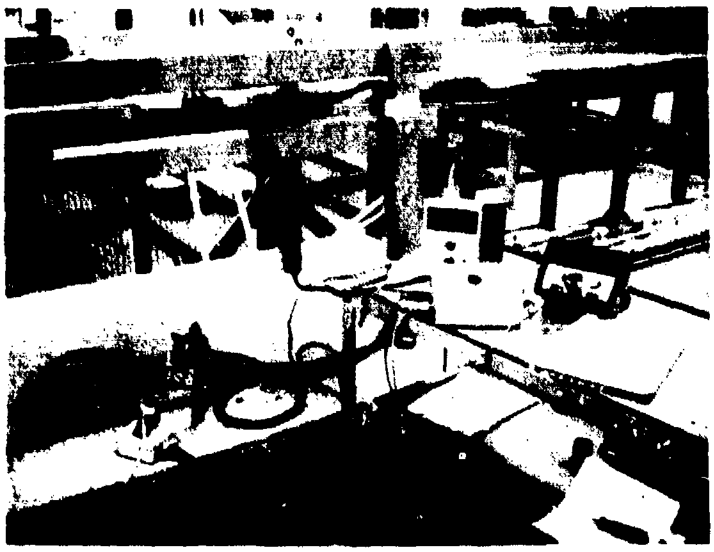

Figure 9. RF parallel plate field simulator.

2. S-band

Antenna - Demornay Bonardi Horn Model L520
Source - Maxson UHF Wide Band Oscillator Mode 1141
Attenuator - ARRA π Line Attenuator Model 4-5414-30

3. X-band

Antenna - Sperry Horn Model 56X1
Narda RF Power Pulser Model 18500 B
Narda Plug-In Model 18500-121

Switching Noise

The instrumentation used in the switching noise testing included the threshold and trip time measurement instrumentation described in the Trip Threshold section; the load; and the relay and relay driver. Figure 10 is a block diagram of the relay and relay driver. This driver can accept a signal from either a random noise generator or from a sine or square wave generator. The amplifier stage at the front end of the circuit squares the signal, and the flip flops with appropriate random noise input divide the frequency to a range acceptable by the relay. The relay used is Potter & Brumfield PR7DXO which has double-pole, single-throw, normally open (DPST-NO) contacts rated at 25 A. Due to the high current and heavy contacts, contact arms, and armature, the maximum operating frequency of the relay is about 30 cycles (opening and closing) per second. When driven from a random source, the relay chatters randomly, with average closure rate less than the maximum closure rate.

Vibration

The following instrumentation provided the driving force and acceleration monitoring during the GFCI vibration testing.

1. Wavetek Sweep Generator, Model 147
2. MB Electronics Power Amplifier, Model 2250
3. MB Electronics Accelerometer, Model 354, Serial 119
4. MB Electronics Zero Accelerometer, Serial 1207
5. MB Electronics Vibration Exciter, Model PM50, Serial 720.

Figure 11 illustrates the instrumentation arrangement.

Hot/Cold Environment

Instrumentation used in this test was the same as that used in the Instrumentation Trip Threshold testing (Figure 7 and Appendix B).

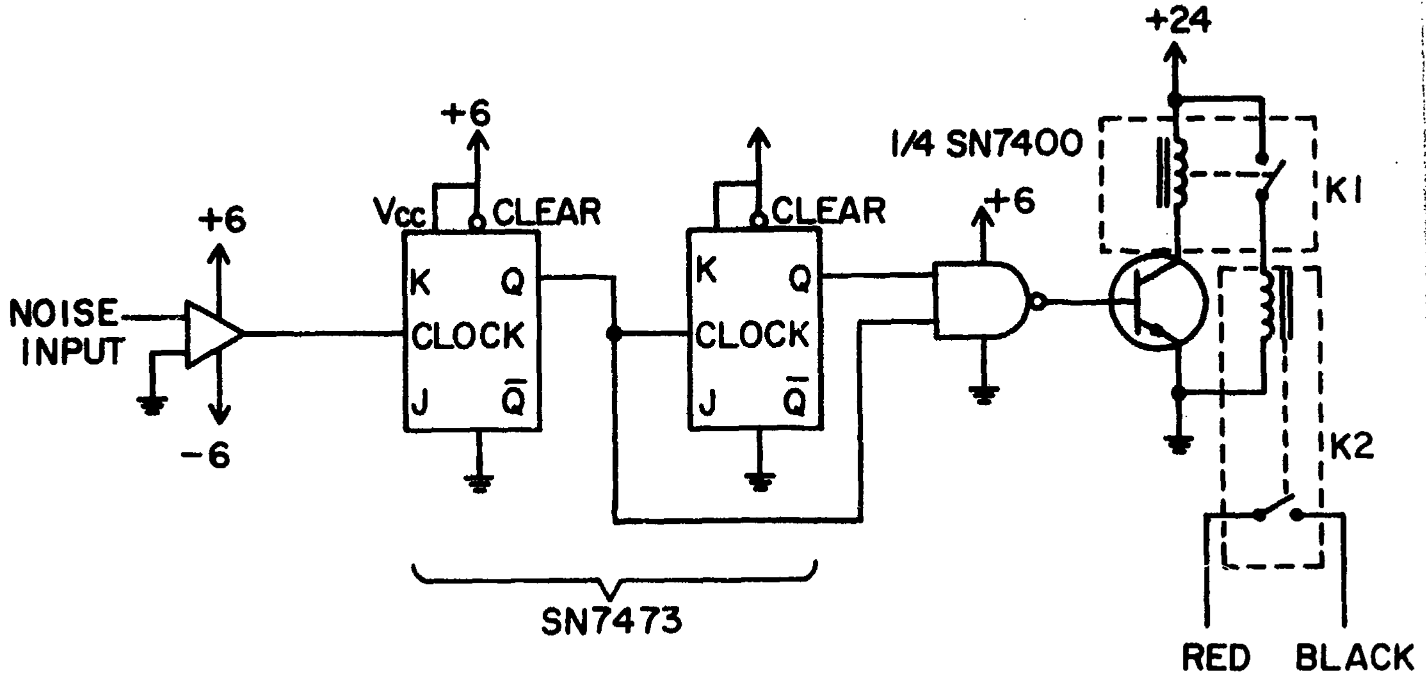

Figure 10. Chattering relay test circuit.

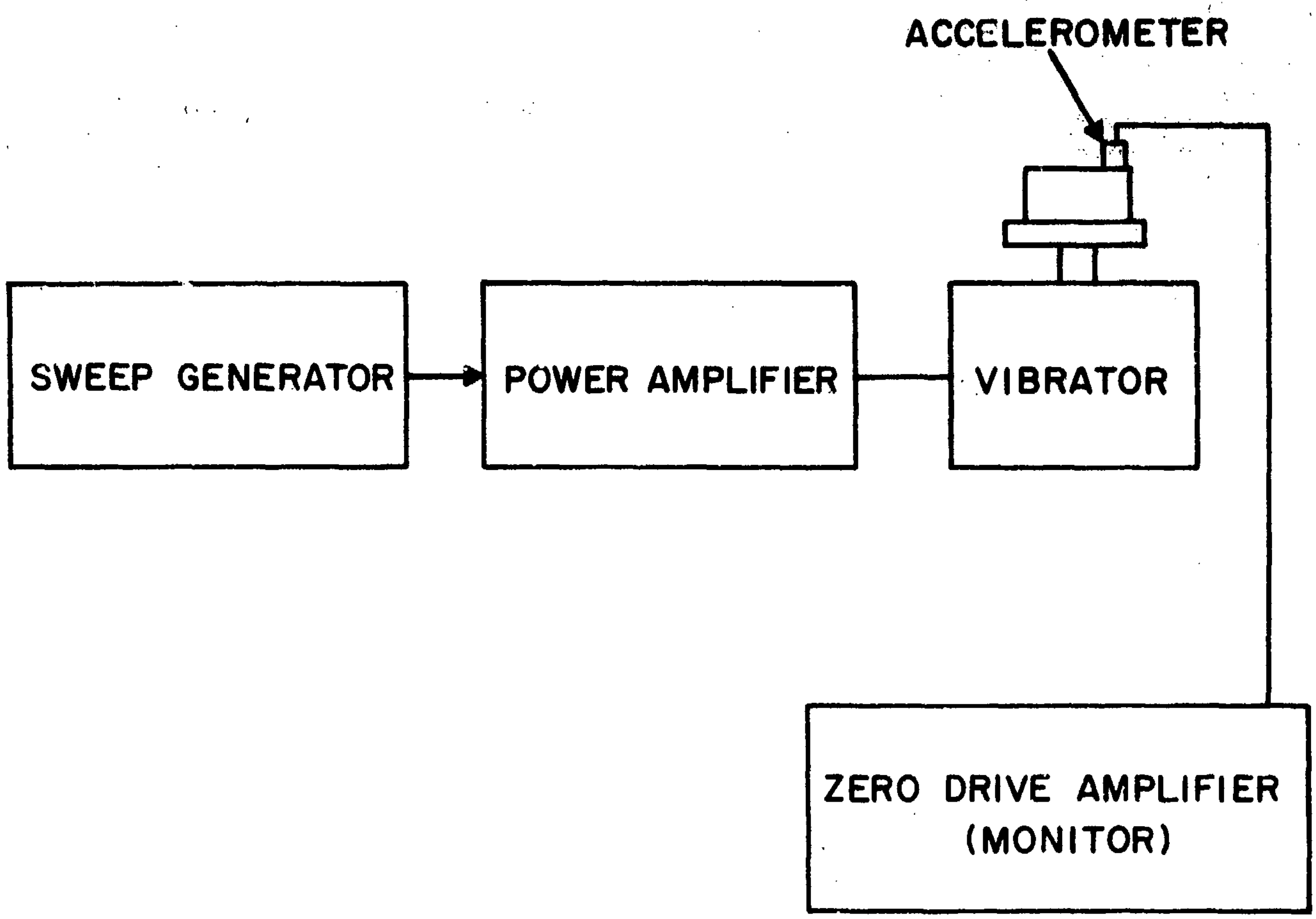

Figure 11. Vibration test setup.

Condensation

GFCIs were tested for susceptibility to condensation by placing them in a specially prepared chamber for 4 weeks. A vaporizer maintained the chamber's relative humidity as close to 100 percent as possible. The temperature in the chamber was maintained at approximately 90°F for the entire period. The test procedure involved applying power to the GFCIs for an operational checkout; no power was applied to the GFCIs except during actual testing. The Model GFT 200 Ground Fault Tester, manufactured by ITE Imperial (Figure 12), was used to determine the GFCI trip current threshold for this test. Figure 13 is an ITE Tester vs. CERL threshold tester calibration curve. It was found that the values read by these two testers differed by less than 1/2 mA. The CERL threshold tester is considered the standard since its mA meter is within required calibration.

The condensation test subjected the GFCI to more continuous exposure than would occur on most construction sites. It is likely, however, that the 4-week test exposure is no more severe than could be expected in 6 months or 1 year on some construction sites.

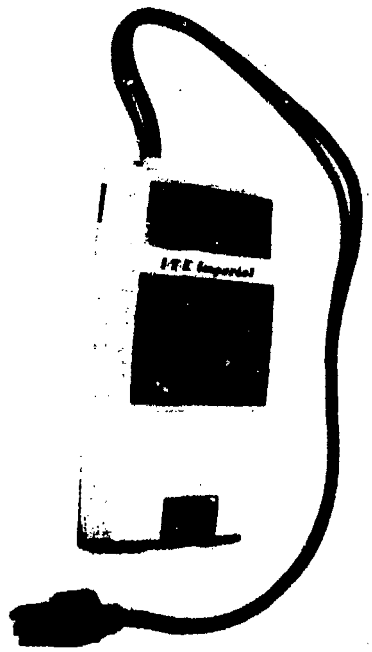

Figure 12. ITE ground fault and leakage current tester.

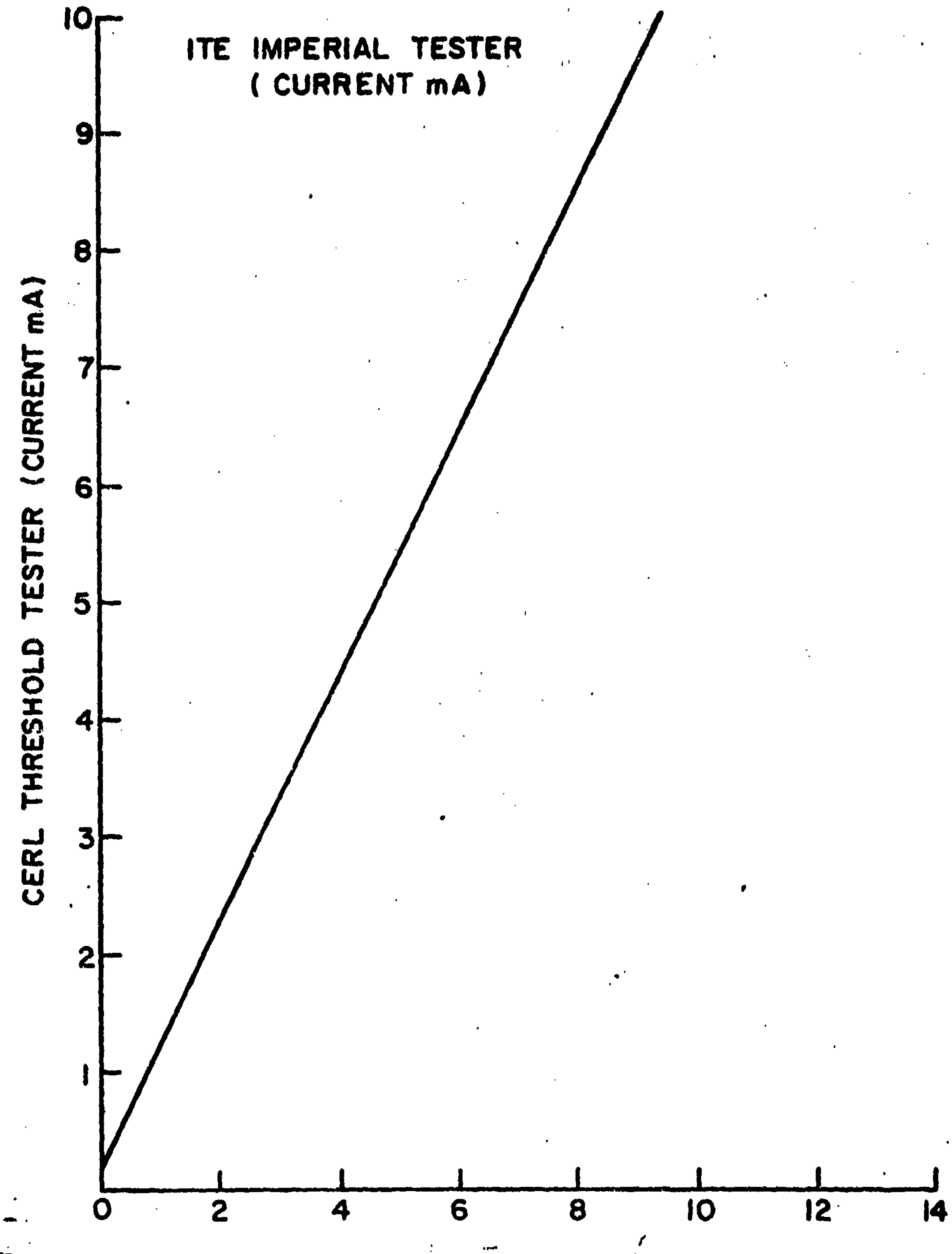

Figure 13. ITE tester vs. CERL threshold tester.

5 SUMMARY OF TEST RESULTS

Trip Threshold

Analysis of the data indicates that the threshold trip value for the GFCIs is relatively close to the 5 ± 1 mA standard for which they were designed. The deviations that occurred are not great enough to significantly change GFCI operations in the field. A statistical analysis of the data was performed, and the results are discussed in Appendix B.

The test substantiated the fact that the GFCIs tested (which were of the latest design) meet the 5 ± 1 mA design parameter. The earliest-model GFCIs were not lab tested. However, it is relatively certain that many of these GFCIs are still installed in the field; trip thresholds measured at visited sites were sometimes as low as 2.6 mA. (NOTE: the lowest trip threshold measured in the lab was 3.34 mA.)

The effect of full load, one-half load, and no load conditions did not significantly affect GFCI operation.

RFI Field Exposure

The RF field exposure test data answers two basic questions:

1. Does the trip threshold vary as a result of exposure of the device to the RF fields?

2. Does the trip time vary beyond acceptable limits as a result of the RF exposure?

Since the trip time did not increase appreciably for any of the devices tested, these data are not presented. However, trip threshold did vary considerably for some units at some frequencies, and the presence of RF fields caused some units to trip. Data summarizing this testing are presented in Appendix B, which shows the trip threshold current at each test frequency. At the lower end of the frequency range (200 kHz), the trip threshold is generally equal (within experimental measurement accuracy) to the trip threshold with no RF field applied. Thus, one can readily see from the test data the effect of fields at higher frequencies. Following is a brief summary of results:

1. Units tested = 61

2. Units which tripped due to fields = 10

3. Units which experienced more than a 25 percent reduction in threshold = 20

4. Units which failed* during test = 2

UHF Microwave

Not all GFCI units underwent all UHF tests, because some were inserted into tests other than UHF microwave and because time constraints limited the number of samples that could be tested.

Summaries of tests performed on all units show the following:

1. Later Model Units

   Quantity tested = 39

   Quantity tripping in the 100 to 500 MHz range = 21

   Quantity tripping at 2400 MHz = 27

   Quantity tripping at 9500 MHz = 6

2. Early Model Units

   Quantity tested at 100 to 500 MHz = 39

   Quantity tripping in 100 to 500 MHz range = 12

   Quantity tested at 2400 MHz = 41

   Quantity tripping at 2500 MHz = 32

   Quantity tested at 9500 MHz = 41

   Quantity tripping at 9500 MHz = 5

   Number of failures during test = 2

4. Number of units not working properly in field = 3

(NOTE: For more detailed test results refer to Appendix B.) These sta stics seem to indicate that the later units are more susceptible to RFI in the 100 to 500 MHz range; however, this is not conclusive because the test's qualitative nature. It should be noted that many units which did trip in this range had to be within 1 in. of the antenna, so the tripping threshold was barely reached. (NOTE: the test is qualitative in that the actual RF exposure may depend on the power wiring configuration to the GFCI.)

A significant outcome of this testing is that it revealed that the latest model Square D Circuit Breaker GFCIs could not be caused to trip or malfunction by any of the tests.

*Failure is defined as loss of ability to function regardless of environment or load.

Switching Noise

The switching noise test data are tabulated in Figure B4. Analysis of these data shows the GFCI to be unaffected by random switching of a resistive load. The inductive load switching produced lower threshold trip values in 42 of the 77 units tested, four of which tripped with no ground fault current and six of which tripped at ground fault currents of less than 4 mA. The randomly switched inductive load (isolation transformer primary with secondary open) approximately simulates a typical AC-DC motor (such as drills and saws) used on construction sites, with intermittent contact of the motor brushes.

Vibration

Only two GFCIs tripped during the vibration testing. A General Electric breaker type No. 6 tripped around 20 G at 50 Hz, and a Federal Pacific break type No. 1 had multiple trips of the following: 10 G at 600 Hz, 23 G at 610 Hz, and 40 G at 700 Hz. Further experimentation showed that the tripping was caused by vibration, and not by electromagnetic interference produced by the vibration transducer. The test indicated that trips from vibration are not necessarily a serious problem, since no trend was produced. It did show, however, that if GFCIs are mounted directly to an engine generator set, they definitely should be vibration-isolated. This can probably be accomplished through inexpensive rubber mounts.

Hot-Cold Environment

Analysis of the data indicates that the GFCI is relatively temperature-independent and that its operation is not greatly affected by the temperature range tested.

Condensation

Appendix B contains a graphical representation of data from condensation tests. The results indicate that GFCI operation is seriously affected by condensation. Seventeen units out of 21 tested--an 80 percent ratio--failed during the test. The failure mode was failure to be reset and failure to trip. The units that did not fail all experienced difficulties such as erratic trips, failure to reset, or total device failure. (See Appendix B.)

Condensation conditions at field sites vary from zero condensation to 100 percent humidity; the latter occurs when the temperature falls below the dew point at night or early morning. This condition, in which water may drip from the GFCI, is produced naturally on a 24-hour cycle, with severity changing from day to day. It is theorized that this natural cyclic condition produces a more severe environment than

the condition under which the tests were conducted. Hot-dry days when dust is deposited on and in the GFCI, early-morning condensation conditions, rain blowing into the GFCI, and contamination from structure washdown, are considered to produce more severe condensation conditions.

6 INFORMATION FROM OTHER AGENCIES

During the GFCI evaluation program, numerous contacts with governmental and industrial agencies revealed that there has been a great deal of testing and evaluation of GFCIs and GFCI-related problems. However, many of the test reports are either not yet available for public release or have been given limited distribution for proprietary reasons. It was therefore necessary to obtain summaries of the programs through telephone conversations. The following discussion summarizes the more important testing programs. (NOTE: The information is provided for background purposes only and was not verified.)

State of California, Department of Industrial Safety

Gene Carlton, an electrical engineer of the California Department of Public Safety, has recently completed a test program for the State of California, which tested 165 single-phase 20-A, 125 V GFCIs obtained from several manufacturers. Tests were performed both in the laboratory and in the field. In the field, GFCIs were used by electrical contractors, utility companies, and suppliers of temporary electrical power systems. GFCIs tested included those with a trip threshold of 5 mA and those with 10 mA. Some conclusions of this testing are:

1. The 5 $\pm$ 1 mA trip level is satisfactory.

2. Nuisance tripping does not really occur. All trips were found to be caused by faulty cords, wiring, tools, or misused or mistreated equipment.

3. The GFCI enhances safety. Statistics show that GFCIs would have prevented most accidents caused by electric shock, including two fatalities in 1971 and two in 1972.

4. If GFCIs are to be used on construction sites, rigid maintenance standards must be observed for all line cords and tools.

5. Workers developed confidence in GFCIs.

Underwriters Laboratories, Inc. (UL)

Electrical Environmental Noise Testing

UL has performed an extensive evaluation of methods to test GFCIs for noise immunity, which involved subjecting many test samples to the noise sources used for testing by the various manufacturers. Based on field performance, all GFCIs tested were rated as "good" or "poor" performers. The results showed a large variation in indicated GFCI performance vs. noise source. The types of sources included chattering relays, chattering relays plus various loads, timer-switched fans and counter, swept RF frequency, capacity discharge, voltage spiker, RF

radiation, and the "showering arc." Some GFCIs were caused to trip by noise, some were made more sensitive, and some were desensitized. The results emphasize the difficulties encountered in attempting to design a test which can perform a conclusive evaluation with regard to guaranteeing performance on construction sites. (NOTE: UL is developing a standard noise test for inclusion in UL 943, but it will not be incorporated for 6 months to 1 year.)

Placement of GFCIs in Selected Homes

A second UL program involved placing GFCIs on selected branch circuits in nearly 100 homes. The homes selected were those of UL engineers, electrical inspectors, and other personnel having electrical system expertise. When trips occurred, the source was investigated. Generally, it was found to result from some defective appliance (often a faulty switch) and was eliminated. This program was completed prior to a concentrated effort by manufacturers to make the devices immune to electro-magnetic interference (EMI).

Surge Tests for GFCIs

UL has developed a procedure for surge testing of GFCIs, and at the same time has tested GFCIs for susceptibility to high-voltage impulses. The test process will be added to the UL Standard 943 as a requirement for all GFCIs.

Line Cord Leakage

UL has also performed related experiments with line cords, in which impure water with known resistivity was used to wet the plugs and receptacles. Different solutions with various resistivities were used, and experiments were performed on several types of connectors and plugs, including the sealed connector with insulating boots. This program revealed that leakage currents can well exceed the GFCI trip threshold, but the sealed connectors do not leak an appreciable amount after being soaked for 48 hours.

International Electro-Technical Commission (IEC)

The IEC has formed several committees to study requirements for GFCIs and circuit breakers, and to prepare specifications. The committees are comprised of representatives from various nations. These committees have not performed actual evaluation programs, but have derived information from other sources of study. Preliminary specifications have been developed for GFCIs with trip thresholds of 5, 15, 30, 100, and 300 mA.

Puget Sound Power and Light Company

Puget Sound Power and Light Company tested several special GFCIs with various trip levels. (General Electric supplied 12 at 15 mA, 3 at 20 mA, and 2 at 35 mA, and a number of UL Standard 5-mA GFCIs). The test was conducted for several months, with results recorded daily. Various contractors were asked to use a 5-mA GFCI and to take precautions of covering and taping the cord connections. When the GFCI tripped, they were to transfer the cord to the receptacle protected by the 15-mA GFCI and note the results. The technique was repeated at other sites for 25- and 35-mA GFCIs.

When long extension cords were used or when precipitation occurred, 5-mA GFCIs were unsatisfactory since they usually resulted in continuous nuisance tripping. The 15-mA GFCI operated satisfactorily on days without precipitation, when cord lengths were less than 300 ft (91.4 m). As adverse weather conditions set in, however, the 15-mA breaker became useless, with resultant nuisance tripping. The 25-mA GFCIs operated satisfactorily most of the time in all weather conditions when cord length was 300 ft (91.4 m) or less. The 35-mA GFCIs operated even more satisfactorily; each time they tripped, the problem was diagnosed as a bad cord or bad equipment.

National Bureau of Standards (NBS)

In March 1976, the National Bureau of Standards released a publication (*Survey of Ground Fault Circuit Interrupter Usage for Protection Against Hazardous Shock*) which summarizes GFCI use in new and old residential buildings and in some other structures. The GFCI report resulted from the NBS program to develop flat conductor cables for buildings. This report, which presents arguments for and against using GFCIs, indicates that (1) for using GFCIs in older buildings, practical problems of leakage current need investigation; (2) additional laboratory and field investigations involving nuisance tripping and reliability aspects of GFCIs should be performed; (3) additional data on shock hazards, particularly to children, the elderly, and the infirm, should be obtained as background information for GFCI technology. The complete report is contained in Appendix C.

7 CONCLUSIONS

The site survey investigation revealed that at 11 of the 12 surveyed Corps of Engineers supervised sites, the contractors considered the GFCI a problem source causing nuisance trips and that its use was not justified by safety hazards. Short GFCI life, high condensation, RF, UHF, microwave fields and long, particularly multiple, extension cords, were all reported as causing problems. The survey indicated that the parameters to be considered in investigational work should include tests to determine the effect of condensation, RF, UHF, microwave fields, hot and cold temperatures, and vibrations of GFCI operation.

Laboratory evaluations have resulted in the following conclusions:

1. Conformance to the 4 to 6 mA trip threshold value specified by UL Standard 943 (November 26, 1975) was verified by the threshold test in the 84 new units tested. (See Trip Threshold Section, Chapter 5).

2. The adverse test conditions in UL Standard 943, paragraph 21.9, do not adequately provide for testing GFCIs used on construction sites under high condensation, vibration, RF, UHF, microwave, or switching noise field conditions.

3. Analysis of the data from the RF, UHF, and microwave tests showed that 99 percent of the GFCIs could be tripped by the presence of certain RF, UHF, microwave fields (see Appendix B). (Frequency and strength of the tripping field varied, depending on GFCI wiring configuration, GFCI parameters, or polarization.) The exception to this--RF, UHF, microwave tripping--was the third-generation Square D GFCI, which appeared to be immune to RF fields at all frequencies.

4. Laboratory investigation of a high-condensation environment produced a large number of GFCI failures (17 out of 21, or 80 percent) (see Condensation Section, Chapter 5). A change in threshold trip values often occurred before the product failed in the laboratory test.

5. Laboratory vibration tests produced two trips out of seven units tested. When GFCIs are used in portable generator applications, vibration isolation should be required.

6. In laboratory tests for switching noise, four out of 111 units were caused to trip; two failed during testing; and 60 percent were made more sensitive to leakage current. (See Switching Noise Section and Figure B4.)

7. No significant changes occurred to the GFCI during the hot-cold cycling. (See Hot/Cold Environment Section, Chapter 5.) It is concluded that no problem exists here.

8. Many GFCI failures occurred during some phase of the condensation and RF, UHF, microwave testing, making it impossible to complete the entire series of tests. (The GFCI either did not reset or would not trip when the test button was pushed or when a fault current of 10 mA was applied.) The overall failure rate was 36 out of 138 tested.

8 RECOMMENDATIONS

1. Even though GFCIs are susceptible to some types of environmental degradation, careful use and expected future improvements are sufficient to recommend continued use on construction sites.

2. All GFCIs currently in use should be carefully protected against exposure to condensation. The GFCI manufacturers should modify the GFCI to provide positive protection from condensation by potting the electronic components or by other techniques.

3. Since GFCIs are not immune to the effects of electrical environmental noise, research and subsequent improvement in this area should be continued by the manufacturers.

4. Since GFCIs currently being used were designed primarily for home or industrial use, a more rugged version should be developed for the construction site. UL should provide a separate set of standards for GFCIs for use on construction sites. These standards should include testing the GFCI under high condensation conditions, and in RF, UHF, microwave, and switching fields.

5. There should be further research by others to investigate the 15-mA GFCI in order to determine its suitability for construction worker protection. Laboratory/field testing should be performed to determine the minimum threshold trip value that is applicable on construction sites. Research should be performed to evaluate current leakage characteristics of standard and waterproof electrical cords, plugs, and connectors. Use of waterproofing sprays and possibilities for developing improved waterproof plugs and connectors should be studied. Final results should determine guidance for field usage.

6. The development of special RF or electrical noise filters which can be used with GFCIs in the field should be investigated by industry. In the case of tools with switching noise that causes trips, a plug-in filter could be inserted in the extension cord. In the case of interference from radio transmitters, filter elements would be required in the load center panel.

7. The use of vibration-isolating mountings should be specified if the GFCI must be mounted in a vibration environment.

APPENDIX A

DETAILED TEST PLAN

Introduction

This test plan describes a 9-month GFCI laboratory testing program performed by CERL to analyze the intended use of GFCIs on construction sites. Corps of Engineers Districts where there were complaints from contractors about costly construction delays from nuisance tripping were contacted and visited. The objectives of the program were to ascertain the capabilities and limitations of the GFCI; to determine what the GFCI's operating parameters should be to accomplish its intended purpose (to protect personnel from fatal shock) without becoming a nuisance through unnecessary tripping; and to determine if there should be a less rigid set of GFCI parameters for use in Corps of Engineers construction.

This test plan describes selection of test samples, selection of tests, test procedures, and data analysis.

Selection of Test Samples

The ground fault protection required by the 1975 National Electric Code for construction sites states that all 120-V, single-phase, 15- and 20-A receptacle outlets which are not a part of permanent wiring shall have ground fault circuit interrupters for protecting personnel. The code does not specify the type of GFCI to be used or its location. The two types of GFCI are:

1. A breaker-type GFCI, which is installed in the power distribution panel rather than a regular circuit breaker, and

2. A GFCI receptacle that is installed instead of a standard wall outlet receptacle.

Test samples were selected on the basis of local availability. Six each of the 20-A, 120-V circuit breaker type were selected from six manufacturers (Square D, Cutler Hammer, General Electric, Federal Pacific, Westinghouse, and Fenco GTE Sylvania). Six each of the plug-in units with an extension cord (receptacle type such as Pass and Seymour, Leviton, and 3M) were also selected. (When possible, only the receptacle portion was procured.) One Harvey Hubbell "Spider" was also selected for testing.

Where possible, test samples from actual site locations where problems had occurred were secured and tested.

Test Selection

Tests were selected to simulate variable circumstances occurring at the job site which would adversely affect GFCI operation: Trip Threshold, RFI, UHF Microwave, Switching Noise, Vibration, Hot/Cold, and Condensation.

Trip Threshold

Leakage from normal line losses and normal tool leakage was characterized. A survey of construction sites has indicated that the primary cause of nuisance tripping is moisture in the form of fog, dew, rain, smog, puddles, etc. The vulnerability of a GFCI to moisture depends on the type of GFCI (circuit breaker or receptacle) and its packaging and location. However, the effect of moisture on extension cords, receptacles, or tools is almost certain to be somewhat detrimental.

Reports from contractors who have investigated GFCIs indicate that the GFCI trip threshold is considerably less than the 5 mA specified by Underwriters Laboratory, Inc. Thus one test selected for the CERL study was the ground-fault simulated test which determines trip threshold and time required for the GFCI to operate at its trip threshold, 5 mA and 10 mA for no load, one-half load, and full load conditions.

RF, UHF, Microwave, Switching Noise

Many complaints from Associated General Contractors had indicated that electrical environmental noise causes nuisance tripping of GFCIs (for example, single frequencies from 5 kHz to 150 MHz generated by buzzer alarms, mechanical switches, food mixers, dishwasher timers, heated combs, concrete vibrators, strong radio frequency fields from transmitters, etc., cause these trips).

Also, discrete RFI testing was performed at selected frequencies throughout the electromagnetic spectrum. MIL-STD 461, *Electromagnetic Interference Requirements for Equipment*, and MIL-STD 462, *Electromagnetic Interference Characteristics, Measurement of Amplitudes*, were used as guides for the testing. EMP testing and broad-band noise spectrum testing were also performed.

Vibration, Hot/Cold Environment, Condensation

One argument presented by Corps of Engineers District personnel is that if the equipment is in good condition, leaky cords and tools will not be a problem on the site. A number of tests were performed on receptacles, extension cords, and portable hand tools to determine their leakage amplitude under selected environmental conditions, including periods of high condensation, temperature extremes, and under vibration conditions.

Test Procedure

Trip Threshold

A device for simulating ground fault leakage was designed and built. This ground fault simulator determined the threshold trip current (defined as the lowest value of ground fault current at which the GFCI will trip) and the outputs for a milliammeter and an event counter. One hundred twenty-Volt AC 60-cycle power for testing was supplied to the testing bench via heavy-duty cord (no. 10/3 wire with ground) through a knife-type, fused, quick-disconnect switch. The GFCI was installed in applicable load center boxes of the type used on a normal installation. The GFCI being tested was connected to a duplex receptacle outlet to which the ground fault simulator was connected. Figure A1 is a schematic of the ground fault simulator.

The threshold current for each GFCI was determined by turning on the GFCI at a condition of 0 fault current, and slowly increasing the current until the GFCI tripped. The milliampere value at which the GFCI tripped was read from a Simpson 2701 Digital Multimeter. The next investigation determined how low a breaker was required for tripping at threshold fault current, designed fault current (5 mA), and twice the designed fault current (10 mA). This was accomplished by setting the desired fault current, automatically starting an event counter when the current was started, and automatically stopping the counter when the GFCI tripped (this was accomplished by using the fault simulator). These two tests were repeated 10 times for each of the following conditions:

Threshold current at no load, one-half load, full load

Designed trip current at no load, one-half load, full load

Twice the designed trip current at no load, one-half load, full load.

RF, UHF, Microwave

Table A1 shows the discrete frequencies that the GFCI was subjected to via placement between a parallel plate's transmission wave guide. The GFCI was subjected to the RF field while ground fault leakage tests were performed. Further tests were performed where energy was directly coupled into the power line. Ground fault leakage tests were performed again, and all data were recorded. (Figure A2 is a schematic of the test setup.

Switching Noise

The most troublesome electrical noise source common to electrical distribution lines is the showering arc noise produced when switches, relays, or commutator contacts are opened and closed. Transient voltage peaks of 17,000 V have been observed; however, a more realistic value is 2000-V peaks. A review of Cutler Hammer Experimental Test Report DL 98-0060, File No. 11.19 indicated that a noise generator similar to theirs

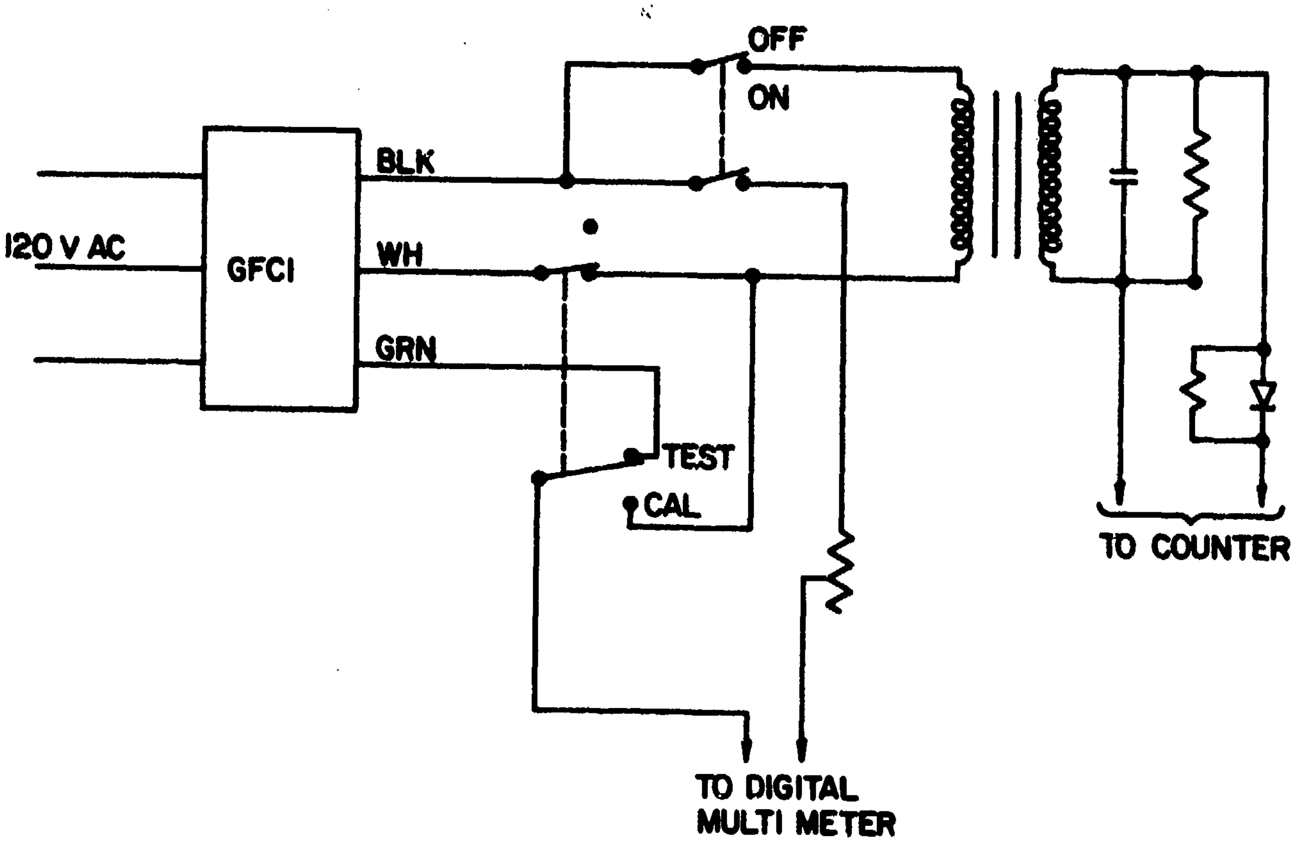

Figure A1. Ground fault simulator.

Table A1

RF Test Frequencies

RFI TEST

- MIL-STD-461, 462 PROCEDURE 50 VOLTS/METER
- FREQUENCY SELECTION

200 KHZ	- LF
500, 1000, 1500 KHZ	- BROADCAST BAND
6, 12 MHZ	- HAM RADIO
27 MHZ	- CITIZENS BAND
65, 100 MHZ	- VHF-TV, FM
170 MHZ	- 2-WAY VOICE
400 MHZ	- UHF TV
2.5, 9.5 GHZ	- RADAR

- OBJECTIVE: TO DETERMINE
  TRIP THRESHOLD
  DESENSITIZED CONDITION
  TIME VARIATION TO TRIP

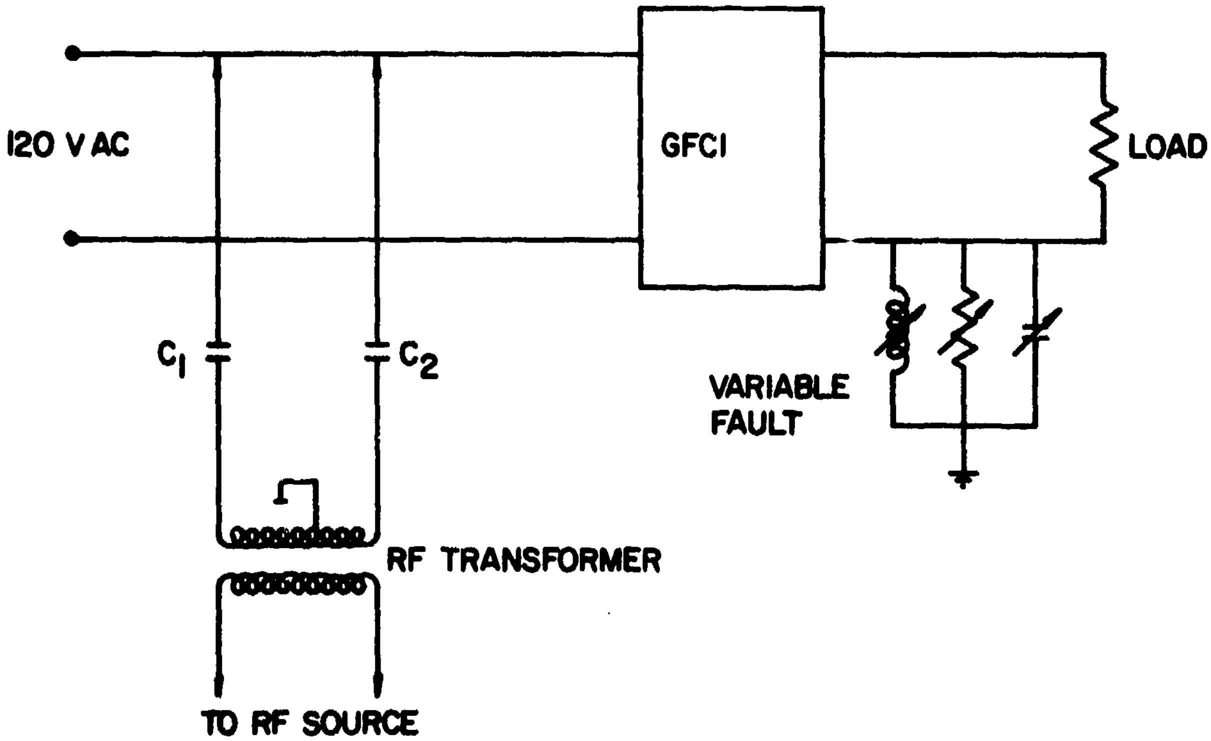

Figure A2. RF test setup.

(Figure A3) or to Underwriters Laboratory's chattering relay noise generator (Figure A4) would be sufficient for CERL tests. The GFCIs were subjected to the noise, and a ground fault current test was performed.

Hot/Cold Environment, Condensation

The ground fault leakage tests were performed while the GFCI was subjected to extreme temperatures of 130°F (54°C) and 32°F (0°C), and conditions of heavy condensation. Leakage tests were also performed on various arrangements of receptacles, extension cords, and extension cord connections. All data were recorded.

EMP

Figure A5 shows that the EMP generator directly couples the pulse into the GFCI circuit voltage pulses; up to 3000 V were applied, and ground fault leakage tests were performed.

Vibration

Since GFCIs are sometimes subjected to vibration (for example, when mounted on portable generator units), Military Standard 810C (Environmental Test Method) was used as guidance for testing the effect of vibration on the GFCI.

Data Analysis

Using the ground fault simulation test data, statistical analysis was performed to determine a statistical threshold trip value for each GFCI brand. Data from the electrical environmental noise test were analyzed to determine if discrete RF frequencies, UHF/microwave, or EMP pulses adversely affected GFCI operation.

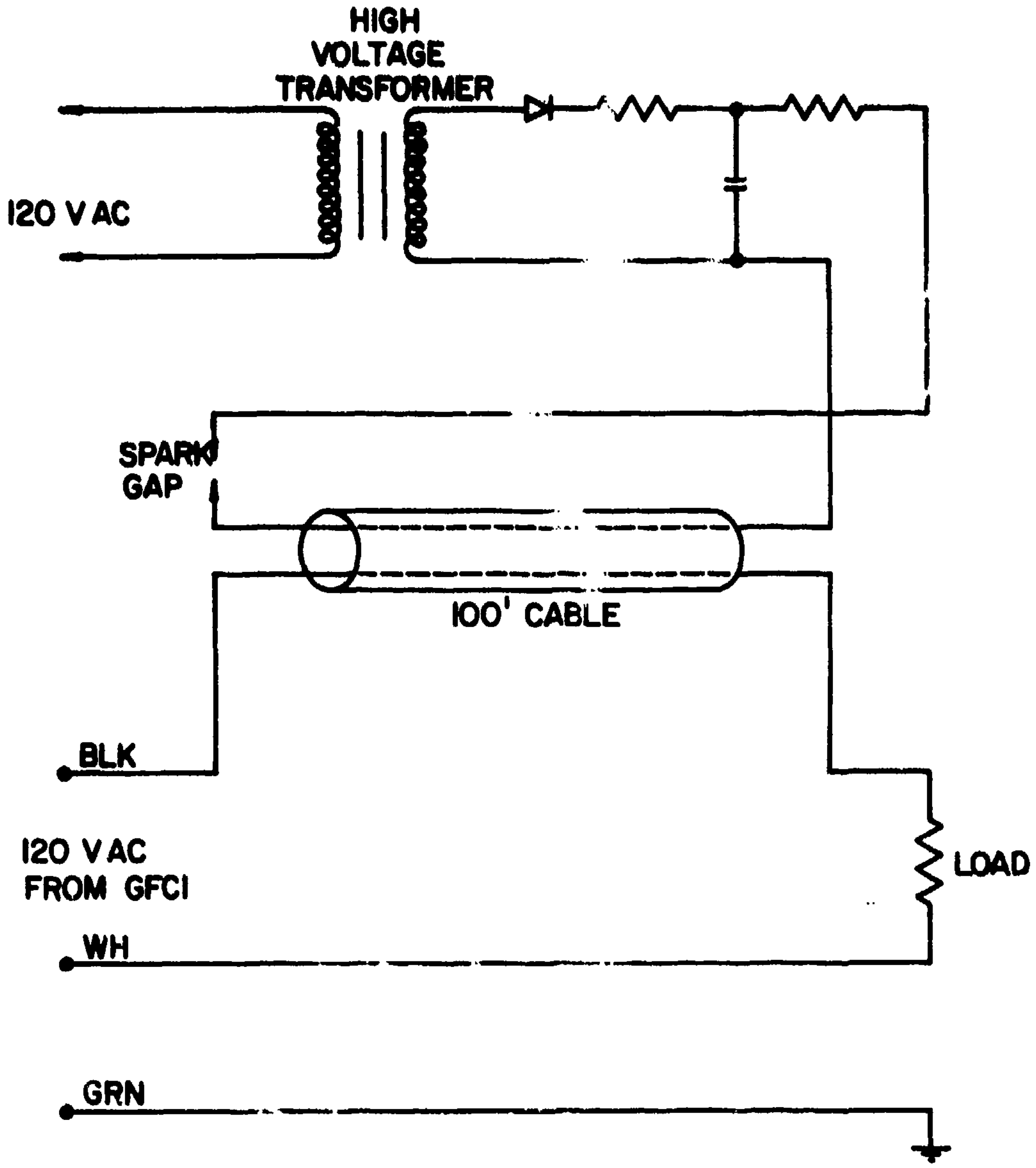

Figure A3. Showering arc noise generator.

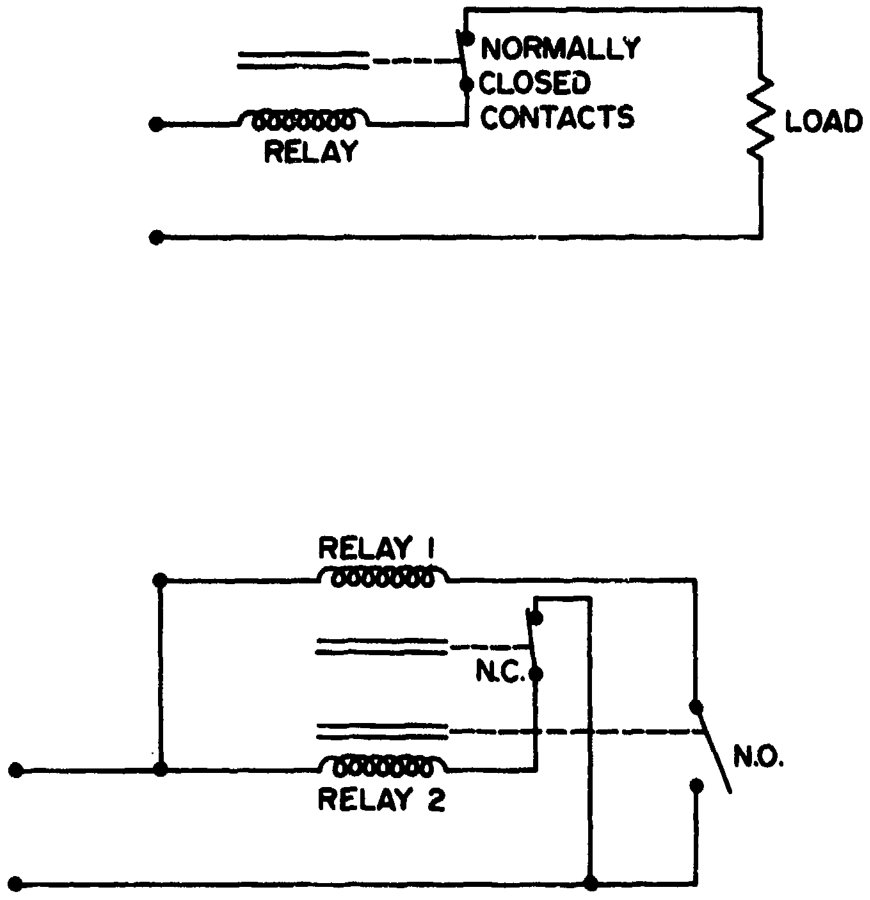

Figure A4. Underwriters Laboratory, Inc. chattering relay noise generator.

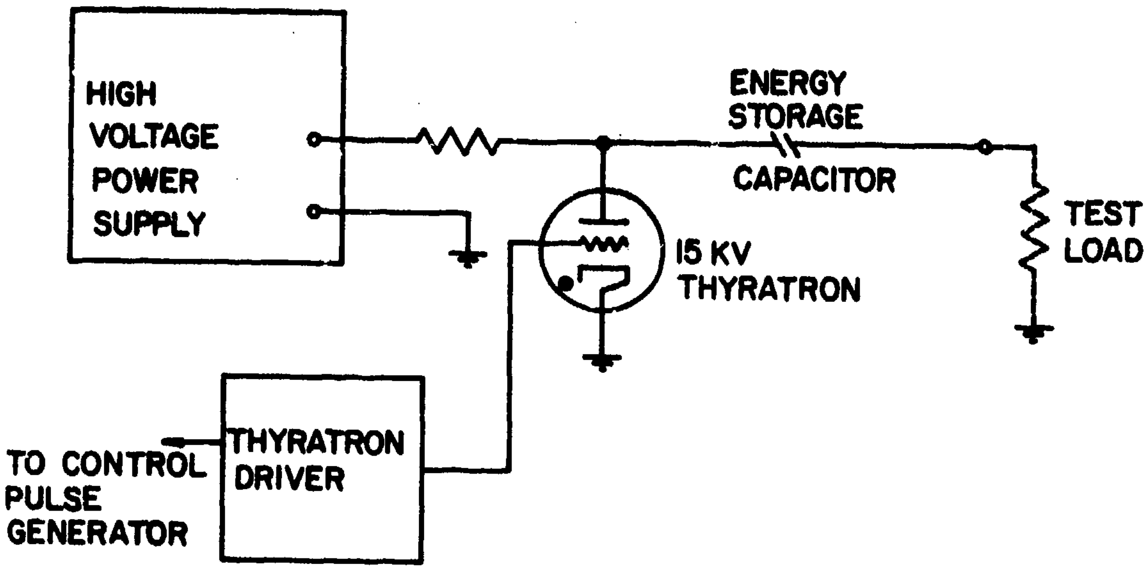

Figure A5. EMP generator.

APPENDIX B

DETAILED DISCUSSION OF LABORATORY TEST WITH DATA AND CURVES

Trip Threshold

Test Approach

The objective of the trip threshold test was to ascertain that the GFCIs available for field installation conformed to Underwriters Laboratory, Inc. Standard for Safety 943. Since, until recently, there were no instruments for measuring trip threshold, no field data were available. Leviton now manufactures a ground fault tester that produces a fault current of more than 6 mA for 1 mA, 2 mA, and 3 mA test positions and for a trip test position. Datametrics, Inc. manufactures a tester that measured line voltage, line leakage, and tool and appliance leakage, and that checks for a grounded neutral. The Bal-Mark ground fault tester was also available on a limited basis.*

Procedure

The GFCI was connected to the tester output. A toggle switch was thrown to the test position and fault current simulation potentiometer slowly increased until the fault was sufficient to trip the GFCI. When the GFCI tripped, the toggle switch was set to read or calibrate, and the GFCI was reset. The trip current value was then read from a milliampere meter connected to the test instrument. This threshold trip value was left constant, while an event counter connected to the test instrument was reset and the test toggle switch was thrown. The event counter counted until the GFCI tripped, and the number of hertz required for tripping was recorded. The procedure was repeated for fault current settings of 5 mA and 10 mA. Ten readings were taken for each fault current setting.

The above procedure was performed for no load conditions, one-half load (10 A flowing through the breaker), and full load (20 A flowing).

Table B1 summarizes the data for the older model units. The ranges of cycles required to trip are given for each load condition for each sample tested. There are no practical differences among the three load conditions (no load, half load, or full load). No statistical analyses were performed on the number of cycles necessary to cause tripping because no practical differences exist; in addition, much of the data could not be analyzed, because in some cases, all readings were identical

*The Bal-Mark Tester, believed to have become available in early 1974, was developed by Mr. Baldwin, electrical inspector at Fort Gordon Resident office, and Mr. Utemark, Assistant Resident Engineer at Fort Gordon.

Table B1

Data Summary from Older-Model Units Tested

Manufacturer	Unit No.	Fault Current (mA)*	Range of Cycles to Trip No Load	Half Load	Full Load
Bryant	1	5.82,5.85,5.88	8-9	9-12	10-13
	2	5.53,5.48,5.36	8-9	7-10	10-11
	3	5.55,5.58,5.57	6-7	8-12	7-9
		5	-	-	-
	1	10	1-2	1-2	1-2
	2	"	2	1-2	1-2
	3	"	1-2	1-2	1-2
Cutler Hammer	1	4.04	7-10	6-11	5-11
	2	4.23	7-11	6-11	6-12
	3	4.15	6-8	6-9	7-10
	4	4.05	10	8-9	6-8
	5	4.98,5.08,5.15	6-9	5-7	5-7
	6	5.06,5.03,5.04	6-9	4-6	5-8
	1	5	3-4	4-5	4-5
	2	"	4-5	4-5	4-5
	3	"	4-5	4-6	3-5
	4	"	3-4	4-5	4-6
	5	"	7-9	-	-
	1	10	2-3	2-3	2-3
	2	"	2-3	2-4	2-3
	3	"	1-3	2-4	2-3
	4	"	2-3	2-4	2-4
	5	"	3	2	2
	6	"	3	2	2

* When three fault currents are given, these are threshold currents with the first one used for no load, the second for half load and the third for full load.

Table B1 (cont'd)

Manufacturer	Unit No.	Fault Current (mA)	Range of Cycles to Trip No Load	Half Load	Full Load
Federal Pacific	1	5.09,5.00,5.00	5-7	8-15	6-8
	2	4.87,4.71,4.54	3-7	13-21	13-29
	3	5.00,4.95,4.95	4-5	5-11	8-10
	4	4.79,4.71,4.71	3-5	4-12	7-11
	1	5	-	-	-
	2	"	3-7	6-11	3-6
	3	"	-	3-7	3-8
	4	"	2-4	2-5	2-5
	1	10	1-4	1-2	1-2
	2	"	1-4	1-2	1-3
	3	"	1-3	1-2	1-2
	4	"	1-2	1-2	1-2
GE Receptacle	1	5.35,5.24,5.19	4-6	3-10	6-11
	2	5.31,5.18,5.14	2-10	2-10	2-7
	3	5.12,5.03,5.01	4-15	8-12	6-8
	4	5.38,5.15,5.14	2-5	2-11	1-5
	5	5.72,5.62,5.56	3-10	2-13	2-7
	6	4.74,4.61,4.53	1-6	2-4	2-4
	6	5	1-3	2-3	2-3
	1	10	1-4	0-2	0-2
	2	"	1-2	1-2	1-2
	3	"	0-1	0-2	0-1
	4	"	0-2	0-1	0-2
	5	"	0-2	0-2	1-2
	6	"	1-2	1-2	1-2
GE	1	5.66	29-33	21-24	17-21
	2	5.65	24-27	33-55	34-57
	3	4.50	28-33	41-52	38-44
	4	5.22	31-36	18-24	20-23
	5	4.07,4.04,4.11	38-45	37-57	32-42
	6	4.07,3.94,3.78	37-44	32-40	30-38
	3	5	18-21	20-24	19-24
	5	"	12-16	11-17	13-14
	6	"	14-17	12-14	11-13

Table B1 (cont'd)

Manufacturer	Unit No.	Fault Current (mA)	Range of Cycles to Trip: No Load	Half Load	Full Load
GE	1	10	6-7	5-9	5-9
	2	"	7-9	7-8	7-12
	3	"	6	5-8	5-9
	4	"	5-7	4-9	6-9
	5	"	3-6	4-5	4-5
	6	"	4-7	4-5	5-6
Leviton	1	4.14,4.10,4.02	11-13	17-19	13-22
	2	4.14,3.92,3.78	13-18	12-19	15-25
	3	4.44,4.22,4.15	14-15	13-25	10-43
	4	3.98,3.85,3.79	12-16	15-33	13-21
	5	4.41,4.33,4.26	11-15	12-53	11-17
	6	4.22,3.97,3.77	10-12	8-11	8-15
	1	5	1-3	2-3	3
	2	"	2-3	1-2	2
	3	"	3-6	2-4	1-3
	4	"	3	1-2	1-2
	5	"	4	3-4	4-5
	6	"	2-4	2	2
	1	10	2-4	1-2	1
	2	"	2-4	1-2	1-2
	3	"	1-4	1-2	1-2
	4	"	2-4	1-2	1-2
	5	"	2-4	1-2	1-2
	6	"	2-4	1-2	0-2
Pass & Seymour	1	3.60,3.58,3.55	147-244	159-211	169-212
	2	3.50,3.64,3.78	153-170	167-235	122-132
	3	5.13,5.09,5.15	55-77	58-156	54-77
	4	3.73,3.67,3.65	164-193	150-197	129-149
	5	3.55,3.24,3.08	138-150	159-198	143-216
	1	5	30-33	31-32	31-33
	2	"	31-33	33-34	33-35
	4	"	34-36	33-35	32-34
	5	"	30-34	28-30	27-28

Table B1 (cont'd)

Manufacturer	Unit No.	Fault Current (mA)	Range of Cycles to Trip No Load	Half Load	Full Load
Pass & Seymour	1	10	12-13	12-13	12-13
	2	"	10-13	10-12	9-11
	3	"	7-10	4-8	6-8
	4	"	10-15	13-15	14-16
	5	"	14-15	13-14	12-13
Sq. D Receptacle	1	3.81,3.67,3.54	50-55	50-62	43-81
	3	3.95,3.96,3.91	60-97	38-50	41-72
	4	4.19,4.15,4.09	45-49	41-47	44-55
	5	4.36,4.41,4.34	45-49	34-40	45-75
	6	4.13,4.00,4.02	39-44	34-39	33-46
	1	5	14-15	11-12	11-12
	3	"	14-15	13-15	12-14
	4	"	18-20	15-17	14-17
	5	"	18-19	16-18	16-17
	6	"	13-18	14-17	13-15
	1	10	5-7	4-5	4-6
	2	"	5-7	4-5	4-5
	4	"	6-7	5-6	5-6
	5	"	7-8	5-6	5-6
	6	"	6-8	5-7	4-6
Square D	1	4.25	3-6	2-6	1-5
	3	4.29	4-9	1-5	1-3
	5	3.46	3-7	2-7	2-5
	6	4.35	3-5	1-3	1-4
	7	3.97,3.94,3.91	5-11	4-10	3-9
	8	3.85,3.76,3.69	6-16	4-14	3-12

Table B1 (cont'd)

Manufacturer	Unit No.	Fault Current (mA)	Range of Cycles to Trip No Load	Half Load	Full Load
Square D	1	5	2-4	1-3	1-3
	3	"	1-4	1-3	1-3
	5	"	1-4	1-2	1-2
	6	"	1-3	1-3	1-3
	7	"	2-4	1-3	1-3
	8	"	2-9	4-6	2-8
	1	10	2-4	1-2	1-2
	3	"	1-3	1-2	1-2
	5	"	1-3	1-2	1-2
	6	"	2-4	1-2	1-2
	7	"	2-3	1-2	1-2
	8	"	4-8	2-7	1-7
Zinsco	1	6.42	1-6	1-2	1-4
	2	3.34	6-10	4-10	2-6
	3	4.22	1-3	1-5	2-3
	4	4.00	1-3	1-6	1-4
	5	3.55,3.61	3-13	2-7	2-17
	6	3.77,4.16,4.34	9-26	2-8	2-14
	2	5	1-2	1-2	1-2
	3	"	1-2	1-3	1-3
	4	"	1-2	1-3	1-3
	5	"	1-2	1-2	1-2
	6	"	1-2	1-2	1-2
	1	10	1-2	1-2	1-2
	2	"	1	1	1
	3	"	1-2	1-2	1-2
	4	"	1-2	1-2	1-2
	5	"	1-2	1-2	1-2
	6	"	1-2	1-2	1-2

or varied only slightly. Note the obvious tendency for smaller values of cycles to cause tripping as the fault current increased.

Data for the newer units are summarized in Table B2. These newer units were tested under no-load condition only. Statistical tests show significant differences for threshold currents (95 percent confidence level) among several of the brands. Note the large range (4.49 to 7.24 mA) and high average (6.18 mA) for Pass and Seymour. Tests were performed to determine if the average threshold values are significantly larger than 5 mA. It can be stated with 99 percent confidence that the average thresholds of AMF Paragon, General Electric, General Electric Receptacle, and ITE are significantly higher than the 5 mA design value for trips occurring within 30 cycles. The data show a trend toward a decreasing number of trip cycles as fault current increases. Also obvious is the decrease in variability of the number of cycles to trip as fault current increases.

Comparisons between the threshold currents (for no load) of the older and newer units showed statistically significant higher currents in the new units for each manufacturer except Cutler-Hammer, GE, and GE Receptacle (Table B3).

RF Field Exposure

Test Approach and Philosophy

Field experimentation with GFCIs has shown that one cause of undesirable tripping is RF energy from radio transmitters. For example, GFCIs were observed to trip when a hand-held transmitter (held about 2 ft from the light) was operated near fluorescent light; although the light fixture was located at a considerable distance from the GFCI panel, simultaneous tripping of several GFCIs in the panel was observed. It is apparent that these trips were caused by currents induced on the circuits and conducted into the GFCI terminals.

The mechanisms for RF susceptibility include exposure of the device to electromagnetic fields as well as exposure to conducted RF. The testing described in this section was to determine the effects of fields on the devices. To perform this test, it was necessary that the device be activated during testing; i.e., that 115 Vac power be applied. This required that wires be attached to the GFCI to serve as an antenna and thus induce RF energy which would be conducted into the GFCI. Thus, the GFCI was subjected to both fields and conducted signals.

When RF energy is present in actual usage, the GFCI will generally be subjected to fields and conducted signals simultaneously. If the GFCI is used in a metallic panel, however, the fields will be attenuated, and exposure will be primarily to conducted signals. In all instances, the combination of shield attenuation and wiring configuration creates a complex system in terms of predicting the actual exposure

Table B2

Data Summary for Newer Units

Manufacturer	Average Threshold (mA)*	Threshold Range (mA)	Threshold Cycle Range	5 mA Cycle Range	10 MA Cycle, Range
American Switch	5.03	4.79-5.24	3-21	2-4	0-2
AMF Paragon	5.20	5.03-5.32	2-7	-	1-2
Cutler Hammer	5.07	4.78-5.40	5-24	4-59	1-2
Federal Pacific	5.49	5.26-5.83	3-12	-	1-2
General Electric	5.43	5.33-5.60	21-29	-	3-5
GE Receptacle	5.22	5.05-5.43	22-30	24-27	3-5
ITE	5.64	5.15-5.87	1-7	-	1-2
Hubble Spider	5.02	4.88-5.29	7-28	6-12	1-3
Leviton	5.07	4.77-5.36	10-30	5-7	1-2
3M Receptacle	4.99	4.77-5.27	27-30	22-30	5-8
Pass & Seymour	6.18	4.49-7.25	22-30	6-8	3-17
Square D	5.35	5.07-5.49	3-10	-	1-2
Square D Receptacle	5.18	5.03-5.45	26-30	25-110	5-7
Bryant	5.56	5,48-6.41	5-10	-	1-3

*Based on six units except for American Switch and Leviton--one unit from each group failed.

Table B3

Threshold Current Comparison Between Older and Newer Model GFCIs

Manufacturer	Type	Number Samples	Average Threshold Current (mA)	Range of Values (mA)
Cutler-Hammer	Old	6	4.42	4.04-5.06
" "	New	6	5.07	4.78-5.40
Federal Pacific	Old	4	4.94	4.79-5.09
" "	New	6	5.49	5.31-5.83
GE Receptacle	Old	6	5.27	4.74-5.72
" "	New	6	5.22	5.05-5.43
GE	Old	6	4.86	4.07-5.66
"	New	6	5.43	5.33-5.60
Leviton	Old	6	4.22	3.98-4.44
"	New	5	5.07	4.77-5.36
Pass & Seymour	Old	5	3.90	3.50-5.13
" "	New	6	6.18	4.49-7.25
Square D Receptacle	Old	5	4.09	3.81-4.36
" " "	New	6	5.18	5.03-5.45
Square D	Old	6	4.03	3.85-4.29
" "	New	6	5.35	5.07-5.49

NOTE: All samples were not subjected to these tests.

level that the GFCI will reach. The following frequencies were selected, based on some anticipated sources:

1. 200 kHz - general low frequency usage
2. 500 kHz - lower end of broadcast band
3. 1000 kHz - center of broadcast band
4. 1500 kHz - top end of broadcast band
5. 6 MHz - near ham band
6. 12 MHz - near ham band
7. 27 MHz - citizens band
8. 65 MHz - mobile bands
9. 100 MHz - FM radio band.

(NOTE: These frequencies may not be present on construction sites and may not be a problem.)

The test concept used was derived from MIL-STD-462, in which a simulator is used to generate a uniform RF field. Field levels used in CERL experiments were approximately the levels recommended as the maximum allowable for exposure of human flesh (10 mW/cm^2). This corresponded to a field intensity level of approximately 200 V/m r.m.s. This field level is greater than that expected from typical hand-held portable transmitters and thus represents a "worst case" test.

Test Procedures

For all RF field exposure tests, the GFCI was installed between the parallel plates and supported by a nonmetallic fixture. All tests were performed without a load on the GFCI, except for the fault simulator described in the Trip Threshold section. At each test frequency, the power level was adjusted to 10 W. An oscilloscope was then used to monitor the RF voltage across the simulator plates. At the higher end of the band, the parallel plate simulator radiated some energy, so that some of the applied power did not reach the termination. The voltage versus frequency between the plates was measured; resultant data are plotted in Figure B1.

During the tests, it was determined that the RF fields affected the fault measurement instrumentation. Therefore, fault current readings were always measured with the RF energy switched off.

At each test frequency, trip threshold and time to trip were measured in nine consecutive operations. In addition, the fault current was set for 10 mA, and the trip time measured in nine consecutive operations.

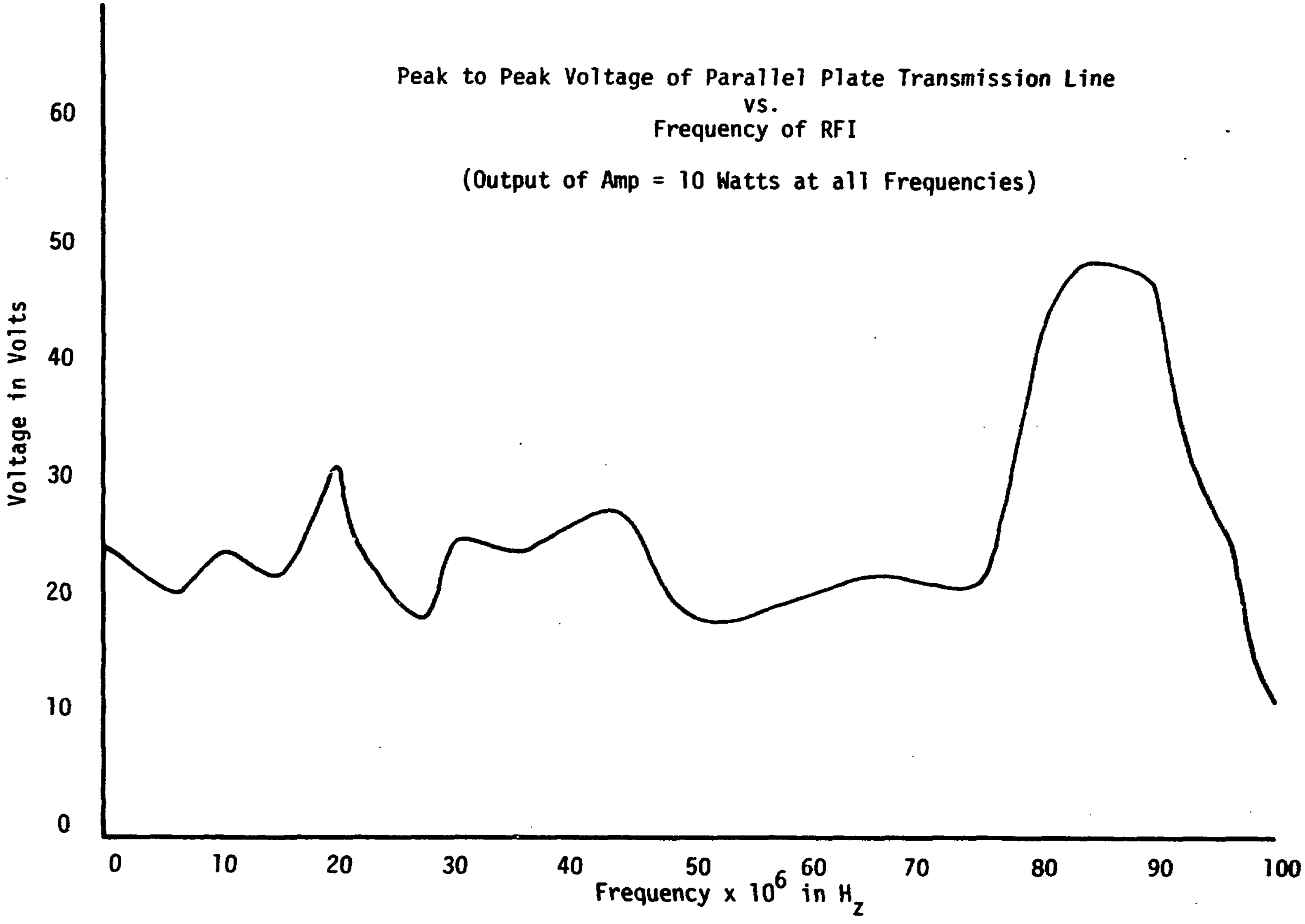

Figure B1. Plot of voltage vs. frequency between plates.

Frequency	Voltage	Voltage
200 kHz	24.2	24.5
500 kHz	24.0	24.0
1000 kHz	23.8	23.5
1500 kHz	23.7	23.2
2000 kHz	23.5	23.2
6 MHz	20.7	20.5
10 MHz	24.2	24.0
15 MHz	21.7	22.0
16 MHz	22.0	23.0
17 MHz	24.0	25.0
20 MHz	31.0	31.0
21 MHz	25.5	25.5
25 MHz	19.0	19.0
27 MHz	18.0	17.7
30 MHz	25.0	24.5
35 MHz	24.2	24.2
40 MHz	26.7	26.5
45 MHz	27.0	27.0
50 MHz	19.0	19.0
60 MHz	20.5	20.2
65 MHz	21.7	22.0
75 MHz	20.0	22.2
76 MHz	24.0	26.3
77 MHz	28.2	31.2
78 MHz	36.0	39.0
85 MHz	47.0	51.0
90 MHz	46.0	48.0
91 MHz	41.0	39.0
92 MHz	32.5	32.5
96.1 MHz	23.5	27.0
97 MHz	16.5	18.2
100 MHz	11.0	10.5

Figure B1 (cont'd)

A summary of results of the parallel plate RF field test is as follows:

	Early	R
Number of units tested	48	49
Number of units tripping	10	6
Units with more than 25 percent reduction in threshold	3	0
Units with more than 25 percent increase in threshold	3	10
Number of units which failed in this test	1	0

A detailed summary of test data is given in Table B4.

UHF Microwave Field Exposure

Test Approach and Philosophy

Construction site reports have noted that UHF transmissions cause GFCIs to trip, especially at the 420 MHz frequency. Therefore, a series of tests was performed to evaluate the effects of UHF and higher frequencies on the GFCI. The parallel plate field simulator (described in the section on instrumentation) becomes inadequate within these frequency ranges due to energy radiation, which causes unpredictable field levels within its test volume. In addition, it becomes extremely difficult to inject current at these frequencies, due to the inductive reactance of GFCI wiring. Therefore, antennas were used to generate the field, and the power applied to them was measured. In the 100 to 500 MHz tests, both forward and reflected power were measured, since the single dipole was used for all frequencies in this band.

At the higher frequencies, the test approach required either a variable attenuator or variable spacing of the test sample from the horn antennas to vary the field exposure levels. The variability was necessary to determine the field levels at which tripping occurred.

The maximum power level chosen for this test was 10 mW/cm^2, established by TB MED 270[5] as the maximum safe level for exposure of human flesh. This level will be generated only very close to the transmitting antennas, but it is conceivable that GFCIs may sometimes be that close. (NOTE: Normally the GFCI will be much farther away from these lower levels and this will not cause problems.)

[5]Technical Bulletin MED 270, *Control of Hazards to Health for Microwave Radiation* (6 December 1975).

Table B4

Trip Threshold vs. Frequency

	200 kHz	500 kHz	100 kHz	1500 kHz	6 MHz	12 MHz	27 MHz	65 MHz	100 MHz
Pass & Seymour Receptacle #1	3.75	3.70	3.78	3.73	3.71	3.76	3.84	3.79	3.72
.. #2	3.71	3.60	3.65	3.67	3.65	3.64	3.70	3.63	1.70
.. #3	5.10	5.08	5.12	5.12	5.10	5.12	5.15	5.00	4.97
.. #4	3.80	3.80	3.80	3.90	3.83	3.82	3.88	3.76	3.79
.. #5	3.68	3.72	3.60	3.63	3.56	3.63	3.60	3.59	3.67
.. #6	Did not Arrive	X	X	X	X	X	X	X	X
Square D .. #1	4.17	4.19	4.11	4.20	3.93	4.14	4.20	4.47	3.75
.. #3	4.15	4.24	4.17	4.25	3.80	4.15	4.17	4.15	3.76
.. #5	3.37	3.41	3.40	3.42	Trips	3.38	3.48	3.74	3.58
.. #6	4.14	4.18	4.14	4.15	3.97	4.15	4.19	4.43	3.91
.. #D1	4.23	4.23	4.24	4.20	4.20	4.22	4.20	4.18	4.21
.. #D2	3.80	3.81	3.80	3.80	3.81	3.80	3.80	3.88	4.03
.. #D3	3.93	3.95	3.94	3.92	3.96	4.05	4.20	4.11	4.10
.. #D4	3.78	3.78	3.78	3.81	3.81	3.80	3.83	4.13	3.75
Square D .. #1	3.77	3.79	3.79	3.79	3.81	3.77	3.82	3.80	3.83
.. #3	3.90	3.95	3.90	3.91	3.90	3.95	3.97	3.97	4.06
.. #4	4.22	4.20	4.21	4.16	4.15	4.18	4.19	4.22	4.18
.. #5	4.33	4.35	4.34	4.37	4.35	4.34	4.36	4.39	4.37
.. #6	4.12	4.11	4.13	4.11	4.04	4.10	4.08	4.12	4.13

NOTE: Square D test samples #D1 through #D4 were extra units of early design vintage which were obtained early in the test program but subjected to only a few tests.

Table B4 (cont'd)

	200 kHz	500 kHz	1000 kHz	1500 kHz	6 MHz	12 MHz	27 MHz	65 MHz	100 MHz
General Electric .. #1	5.66	5.62	5.63	5.65	5.63	5.66	5.68	5.63	5.36
.. #2	5.29	5.33	5.30	5.32	5.30	5.29	5.29	5.38	5.19
.. #3	4.41	4.42	4.38	4.40	4.39	4.39	4.37	4.44	4.43
.. #4	5.23	5.24	5.25	5.25	5.28	5.29	5.22	5.15	5.23
.. #5	3.95	3.97	3.96	3.97	3.97	3.97	3.94	3.92	3.85
.. #6	3.97	3.97	4.00	4.01	4.00	3.99	4.00	4.15	3.85
GE Receptacle .. #1	5.12	5.12	5.12	5.11	5.11	5.11	5.12	5.20	5.16
.. #2	5.34	5.30	5.30	5.33	5.28	5.30	5.36	5.25	4.87
.. #3	5.25	5.22	5.22	5.26	5.21	5.23	5.20	5.15	4.90
.. #4	5.36	5.35	5.36	5.37	5.36	5.36	5.42	5.35	5.20
.. #5	5.65	5.63	4.60	5.63	5.60	5.61	5.61	5.56	5.20
.. #6	4.65	4.67	4.71	4.66	4.69	4.66	4.64	4.65	4.66
GE Receptacle .. #R1	5.49	5.44	5.38	5.19	4.21	6.08	4.73	5.18	5.52
.. #R2	5.27	5.23	5.21	5.17	5.03	5.74	6.28	5.53	4.81
.. #R3	5.10	5.14	5.06	5.12	5.00	5.34	6.28	5.13	5.55
.. #R4	5.30	5.26	5.37	5.23	5.10	5.77	6.63	6.86	6.07
.. #R5	5.42	5.44	5.42	5.39	4.98	5.79	7.92	7.47	5.98
.. #R6	5.22	5.20	5.19	5.25	5.20	5.33	5.86	5.91	5.97

Table B4 (cont'd)

	200 kHz	500 kHz	1000 kHz	1500 kHz	6 MHz	12 MHz	27 MHz	65 MHz	100 MHz
Zinsco .. #1	6.88	6.87	6.29	4.28	3.10	6.50	7.90	Trip	Trip
.. #2	3.32	3.31	3.31	3.32	3.28	3.30	3.32	Trip	Trip
.. #3	4.18	4.16	3.93	2.70	4.07	4.46	5.20	Trip	Trip
.. #4	4.17	4.12	3.87	3.06	4.06	4.25	4.81	Trip	Trip
.. #5	3.47	3.45	3.48	3.46	3.45	3.42	3.44	Trip	Trip
.. #6	3.70	Failed	-	-	-	-	-	-	-
Cutler Hammer #1	3.97	4.02	4.07	4.05	4.09	3.5-4.5	Trips	Trips	Trips
.. #2	4.23	4.25	4.22	4.13	4.23	4.38	Trips	3.64	Trips
.. #3	4.03	4.07	4.13	4.01	4.05	4.13	Trips	Trips	Trips
.. #4	3.99	4.00	4.06	4.04	4.01	4.11	Trips	3.63	Trips
.. #5	4.97	4.97	4.97	4.98	4.98	4.97	4.96	4.92	4.87
.. #6	5.05	5.03	5.03	5.06	5.09	5.05	5.09	5.03	5.00
AHF Paragon	5.37	5.29	5.29	5.27	5.29	5.27	5.21	5.31	5.22
.. #R2	5.26	5.24	5.30	5.19	5.19	5.20	5.21	5.31	Trips
.. #R3	5.49	5.45	5.43	5.42	5.42	5.43	5.39	5.45	5.36
.. #R4	5.41	5.41	5.40	5.45	5.40	5.40	5.40	5.41	5.46
.. #R5	5.09	5.10	5.08	5.12	5.11	5.09	5.09	5.10	5.06
.. #R6	5.42	5.38	5.40	5.34	Trips	5.38	5.40	5.33	5.40
Leviton Recptacle	4.11	4.10	4.10	4.11	4.17	4.16	4.16	4.16	4.19
.. #2	4.15	4.16	4.17	4.17	4.20	4.19	4.10	4.17	4.13
.. #3	4.32	4.32	4.35	4.40	4.38	4.40	4.40	4.36	4.32
.. #4	3.93	3.96	3.96	3.95	3.95	3.97	3.92	3.91	3.93
.. #5	4.45	4.45	4.49	4.50	4.52	4.51	4.51	4.52	4.51
.. #6	4.20	4.22	4.27	4.23	4.28	4.27	4.27	4.28	4.38

Table B4 (cont'd)

	200 kHz	500 kHz	1000 kHz	1500 kHz	6 MHz	12 MHz	27 MHz	65 MHz	100 MHz
Leviton Recptacle .. #R1	5.08	5.11	5.14	5.18	5.17	5.21	5.14	5.11	5.21
.. #R2	4.95	4.96	4.87	4.92	4.87	4.89	4.89	4.91	4.96

Table B4 (cont'd)

Type	Threshold	200 kHz	500 kHz	1000 kHz	1500 kHz	6MHz	12MHz	27MHz	65MHz	100 MHz
Square D Recept #R1		5.23	5.27	5.35	Reset button malfunctioned ----------					
#R2		5.21	5.25	5.25	Reset button malfunctioned---------- 5.25					
#R3		5.59	5.63	5.73	Reset button malfunctioned----------					
#R4		5.05	5.06	5.02	Reset button malfunctioned---------- 5.02					
Bryant #R1		5.76	5.73	5.73	5.73	5.75	5.51	4.92	4.95	5.42
#R2		5.45	5.47	5.46	5.46	5.47	5.28	5.03	5.11	Trips
#R3		5.49	5.49	5.53	5.50	5.50	5.34	5.19	4.52	4.65
American Switch #R1		5.09	5.05	5.00	4.95	5.05	4.94	5.21	4.47	4.36
#R2		-	-	-	-	-	-	-	-	-
AMF Paragon Recept. #R1		5.37	5.29	5.29	5.27	5.29	5.27 buzzes	5.21	5.31	5.22
#R2		5.26	5.24	5.20	5.19	5.19	5.20 buzzes	5.21 buzzes	5.31 buzzes	Trips

Table B4 (cont'd)

Type	Threshold	200 kHz	500 kHz	1000 kHz	1500 kHz	6MHz	12MHz	27MHz	65MHz	100 MHz
AMF Paragon Recept.										
#R3		5.49	5.45	5.43	5.42	5.42	5.43	5.39	5.45	5.36
#R4		5.41	5.41	5.40	5.45	5.40	5.40	5.40	5.41	5.46
#R5		5.09	5.10	5.08	5.12	5.11	5.09	5.09	5.10	5.06
#R6		5.02	5.38	5.40	5.34	Trips	5.38	5.40	5.33	5.40
Cutler Hammer										
#R4		5.21	5.21	5.20	5.21	5.17	5.21	5.23	5.14	5.19
#R5		4.96	4.96	4.95	4.98	4.93	4.93	4.94	4.98	4.92
#R6		5.20	5.20	5.23	5.24	5.16	5.28	5.19	5.09	4.92
Federal Pacific										
#R1		5.75	5.77	5.75	5.75	13.29	6.54	6.03	6.10	5.92
#R2		5.81	5.81	5.80	5.81	14.33	7.00	6.34	6.21	6.18
#R3		5.33	5.35	5.35	5.32	10.01	5.63	5.46	5.52	5.35

Table B4 (cont'd)

Type	Threshold	200 kHz	500 kHz	1000 kHz	1500 kHz	6MHz	12MHz	27MHz	65MHz	100 MHz
GE										
#R4		5.27	5.29	5.26	5.26	5.36	5.34	5.57	8.46	6.17
#R5		5.35	5.38	5.36	5.35	5.27	5.33	5.46	5.22	6.62
#R6		5.33	5.36	5.37	5.35	5.44	5.39	6.06	7.88	7.25
GE Recept.										
#R1		5.49	5.44	5.38	5.19	4.21	6.08	4.73	5.18	5.52
#R2		5.27	5.23	5.21	5.17	5.03	5.74	6.28	5.53	4.81
#R3		5.10	5.14	5.06	5.12	5.00	5.34	6.28	5.13	5.55
#R4		5.30	5.26	5.37	5.23	5.10	5.77	6.63	6.86	6.07
#R5		5.42	5.44	5.42	5.39	4.98	5.79	7.92	7.47	5.98
#R6		5.22	5.20	5.19	5.25	5.20	5.33	5.86	5.91	5.97
ITE										
#R1		5.37	5.49	5.57	5.67	5.64	7.88	6.50	6.55	6.89
#R2		5.30	5.34	5.34	5.40	5.89	8.10	5.52	6.24	7.95
#R3		5.64	5.68	5.67	5.77	5.87	8.53	6.08	6.78	6.76

Table B4 (cont'd)

Type	Threshold	200 kHz	500 kHz	1000 kHz	1500 kHz	6MHz	12MHz	27MHz	65MHz	100 MHz	
Leviton Recept #R1		5.08	5.11	5.14	5.18	5.17	5.21	5.14	5.11	5.21	
#R2		4.95	4.96	4.87	4.92	4.87	4.89	4.89	4.91	4.96	
#R3		5.33	5.34	5.36	5.41	5.45	5.47	5.44	5.43	5.41	
#R4		5.09	5.13	5.13	5.17	5.22	5.21	5.23	5.25	5.22	
#R5	Failed during threshold test ----------										
#R6		4.97	4.95	4.99	5.03	4.98	5.01	4.99	5.01	5.00	
3M Recept. #R1		5.30	5.26	5.29	5.24	5.05	5.25	5.23	5.24 (trips)	5.30 (trips)	
#R4		4.93	4.93	4.94	4.92	4.51	4.88	4.85 (trips)	4.87 (trips)	4.86 (trips)	
#R6		4.97	4.98	5.00	5.00	4.70	4.92	4.93	trips	trips	noise trips also
Pass and Seymour Recept.											
#R1		6.66	6.51	6.57	6.45	5.62	6.55	6.51	6.50	6.43	
#R2		5.51	5.58	5.65	5.77	5.63	5.72	5.70	5.75	5.28	

Table B4 (cont'd)

Type	Threshold	200 kHz	500 kHz	1000 kHz	1500 kHz	6MHz	12MHz	27MHz	65MHz	100 MHz
Pass and Seymour Recept.										
#R3		6.35	6.58	6.39	6.40	6.41	5.28	5.24	5.29	5.30
#R4		6.75	6.74	6.64	6.80	6.91	6.80	6.82	6.62	6.60
#R5		7.23	7.41	7.30	7.45	7.35	7.69	7.62	7.58	7.08
Square D										
#R4		5.20	5.20	5.19	5.19	5.17	5.19	5.17	5.19	5.19
#R5		5.33	5.31	5.31	5.29	5.28	5.32	5.34	5.33	5.33
#R6		5.29	5.35	5.33	5.37	5.35	5.38	5.40	5.36	5.37

Personnel should not be working in a construction area if power levels are greater than 10 mW/cm^2. Therefore, testing at significantly higher levels is believed unnecessary.

In the range of radar frequencies, an S-band frequency of 2500 MHz and an X-band frequency of 9500 MHz were chosen for device evaluation. In both cases, horn antennas were used to generate the fields. At 9500 MHz, the signal source provided only pulsed energy of 500 W peak with 1 msec duration and .001 duty cycle. The average power was therefore 0.5 W. At 2500 MHz, the source could provide continuous wave (CW) pulse modulation, or square wave modulation. The source power was 10 W CW, or 10 W peak for pulse modulation, with average power reducing with duty cycle.

In the 100 to 500 MHz frequency range, the source power was approximately .25 W, depending on frequency. A Thruline wattmeter was used to measure both reflected and forward power to the antenna, since the antenna was not tunable. The source provided CW only.

Test Procedure

The GFCIs were connected to input 120 Vac power, using a conventional rubber-jacketed, three-wire line cord. The rubber insulation jacket was stripped back, leaving about 4 in. (10 cm) of the individual insulated wires exposed. Thus, when power was connected to the GFCI, wire loops were formed with approximately 4-in. (10 cm) diameters.

All tests were performed without a load on the GFCI. The GFCI was placed in the strongest portion of the field from the antennas for each frequency, and rotated through all planes to see if the RF energy would cause it to trip. If tripping occurred, then the power was either reduced, or the GCFI was moved further away from the antenna.

When testing was performed in the 100 to 500 MHz range, the frequency was slowly increased from 100 MHz, with the GFCI in close proximity to the antenna. The GFCI was then rotated to various angles as the frequency was increased. If a trip occurred, the band of frequencies causing it was determined.

At 2500 and 9500 MHz, the GFCI was rotated in front of the horn and observed for trips. If tripping occurred, the signal level was reduced (in the 2500 MHz test) or the GFCI was moved further from the antenna (in the 9500 MHz test) to determine the minimum signal strength required to cause tripping.

Some devices were tested at 2500 MHz with square wave (on-off) or sine modulation at 400 and 1000 Hz. Table B5 summarizes UHF microwave test data.

Table B5

Summary of UHF/Microwave Field Exposure Test Data

GFCI TYPE & SAMPLE #	#	100-500 mHz TEST			2500 mHz TEST			9500 mHz TEST		
		TRIP	FREQ RANGE mHz	DISTANCE TO ANT	TRIP	CW POWER (WATTS)	1000 Hz MOD PWR (WATTS)	TRIP	DIST TO ANTENNA	REMARKS
3M (Recept)	#R1									
	#R2	X	200-360	<1 in.	*			--		*Buzzed then failed
	#R3	X	*210-350	<1 in.	*X	0.08	0.08	--		*Buzzed
	#R4									
	#R5									
	#R6									
Pass & Seymour	#R1									
	#R2	X	200-360	<1 in.	*X	0.25	0.25	X	5 in.	*Became hot during test
	#R3									
	#R4	X	*200-370	<1 in.	**X	0.032	0.016	X	9 in.	*Chatters ** overheats
	#R5	X	195-350	<1 in.	X	0.08	0.06	--		
	#R6									
	#1	--			--			--		
	#2									
	#3	--			X	1.6	1.6	--		
	#4	--			*X	2.5	1.25	--		*Can't be set when in field
	#5	--			X	0.6	0.8	--		
	#6									

Table B5 (cont'd)

GFCI TYPE & SAMPLE #	100-500 mHz TEST			2500 mHz TEST			9500 mHz TEST		
	TRIP	FREQ RANGE mHz	DISTANCE TO ANT	TRIP	CW POWER (WATTS)	1000 Hz MOD PWR (WATTS)	TRIP	DIST TO ANTENNA	REMARKS
Square D (CBR) #D1	X	225-255	<1 in.	X	8	10	--		
#D2	X	195-250	<1 in.	X	4	1.6	--		
#D3	X	247-280	<1 in.	X	3.5	1.6	--		
#D4	X	228-248	<1 in.	X	1.6	0.8	--		
Square D (CBR) #8	----FAILED----								
#7	--			--			--		
#1	--			X	0.4	0.9	--		
#2									
#3	--			X	--	10	--		
#4									
#5	--			X	0.18	0.10	--		
#6	--			X	2.5	2.5	--		
Square D (Recept)									
#R1	--			X	0.022	0.02	--		
#R2	--			X	5	0.16	--		
#R3									
#R4									
#R5	--			X	0.08	0.075	--		
#R6									
Square D (CBR) #R1	--			--			--		
#R2	--			--			--		
#R3	--			--			--		
#R4	--			--			--		
#R5	--			--			--		
#R6	--			--			--		
Square D (Recept)									
#1	--			X	0.45	1.8	--		
#2									
#3									
#4									
#5	--			X	0.8	1.0	--		
#6	--			X	0.6	1.0	--		

X = Trip, -- = No Trip

Table B5 (cont'd)

GFCI TYPE & SAMPLE #		100-500 mHz TEST			2500 mHz TEST			9500 mHz TEST		
		TRIP	FREQ RANGE mHz	DISTANCE TO ANT	TRIP	CW POWER (WATTS)	1000 Hz MOD PWR (WATTS)	TRIP	DIST TO ANTENNA	REMARKS
ITE (CBR)	#R1	X	200-370	1 in.	X	5	5	--		
	#R2									
	#R3	X	*145-500	<1 in.	X	.56	3.2	--		*Certain Frequencies only
	#R4									
	#R5	X	190-300	<1 in.	X	2.8	2.8	--		
	#R6									
Leviton	#1	--			X	0.75	0.75	X	30 in.	
	#2	--			X	0.95	0.25	X	32 in.	
	#3	--			X	0.95	0.3	X	33 in.	
	#4									
	#5	--			X	1.6	0.55	X	5 in.	
	#6	--			X	6	0.8	X	20 in.	
	#R1	X	330-360	<1 in.	X	.08	0.1	X	4.5in.	
	#R2	X	215-275	<1 in.	X	.045	0.095	X	3 in.	
	#R3									
	#R4									
	#R5									
	#R6	X	345-360	<1 in.	X	0.03	0.025	X	3 in.	

Table B5 (cont'd)

GFCI TYPE & SAMPLE #	100-500 mHz TEST			2500 mHz TEST			9500 mHz TEST		
	TRIP	FREQ RANGE mHz	DISTANCE TO ANT	TRIP	CW POWER (WATTS)	1000 Hz MOD PWR (WATTS)	TRIP	DIST TO ANTENNA	REMARKS
General Electric #1				X	0.25	0.025	--		
" " #2				X	0.22	0.08	--		
" " #3				X	0.08	0.09	--		
" " #4	X	163-500	0-8 in.	X	0.025	0.40	--		
" " #5	X	265-500	1 in.	X	0.12	0.16	--		
" " #6	X	200-500	1 in.						
" " #R1	X	340-360	<1 in.	X	5.5	0.5	--		
#R2	--			X	6	7			
#R3	X	*220-500	<1 in.	X	3	6	--		at certain frequencies only
#R4									
#R5									
#R6									
GE Receptacle #1	--			X	3.5	3.5	--		
#2	--			X	10	5	--		
#3	--			X	10	10	--		
#4				X	10	6	--		
#5				--			--		
#6				X	9	5	--		
#R1	X	215-500	<1 in.	X	2.1	0.6	--		
#R2									
#R3	X	335-355	<1 in.	X	.8	.23	--		
#R4									
#R5	X	200-500	<1 in.	X	1.6	0.95	--		
#R6									

Table B5 (cont'd)

GFCI TYPE & SAMPLE #		100-500 mHz TEST			2500 mHz TEST			9500 mHz TEST		
		TRIP	FREQ RANGE mHz	DISTANCE TO ANT	TRIP	CW POWER (WATTS)	1000 Hz MOD PWR (WATTS)	TRIP	DIST TO ANTENNA	REMARKS
Bryant	#1	--								
"	#2	--			X	4	2.5	--		
"	#3	--			X	5	2	--		
"	#4									
"	#5									
"	#6									
Cutler Hammer	#1									
" "	#2									
" "	#3				X	.1	2	--		
" "	#4	X	240-500							
" "	#5	X	290-390		X	6	4	--		
" "	#6	X	260-400		X	10	10	--		
" "	#R1	--			--			--		
" "	#R2	--			X	1.8	1	--		
" "	#R3	X	180-250		--			--		
" "	#R4	X	205-295		--			--		
" "	#R5									
" "	#R6									
Federal Pacific	#1	--								
" "	#2	--								
" "	#3	--			X*	3.25	3.25	--		Test Button inop. during RFI.
" "	#4				X	4	4	--		
" "	#5									
" "	#6									
" "	#R1	--			X	1.6	6	--		
" "	#R2	--			X	1.6	2.5	--		
" "	#R3									
" "	#R4									
" "	#R5									
" "	#R6	--			X*	6	8	--		Test Button Inop. during RFI.

Table B5 (cont'd)

GFCI TYPE & SAMPLE #		100-500 mHz TEST			2500 mHz TEST			9500 mHz TEST		
		TRIP	FREQ RANGE mHz	DISTANCE TO ANT	TRIP	CW POWER (WATTS)	1000 Hz MOD PWR (WATTS)	TRIP	DIST TO ANTENNA	REMARKS
Zinsco	#1	X	135-500	14 in.						
"	#2									
"	#3	X	140-500	<1 in.				Failed		
"	#4									
"	#5				X	0.4	0.1	--		

Switching Noise Tests

Test Approach and Philosophy

Field experience with GFCIs has indicated that one cause of undesirable tripping has been the electrical noise associated with certain tools. Generally the tool(s) uses a rotating armature with commutator (or slip rings) and electrical brushes to make contact with the rotating elements. At the point of contact between the brushes and the rotating element, some arcing generally occurs as circuits make or break. Relatively high levels of switching noise are associated with the arcing.

Arcing is caused by generation of very high voltages when contact is broken. The electrical contacts will be switching a load which may be almost entirely inductive, and will always contain inductive elements. Since the voltage across a pure inductor is defined by

$$V_l = L \frac{di}{dt}, \qquad \text{[Eq B1]}$$

where V_l = voltage across the inductor

L = inductance in henries

$\frac{di}{dt}$ = time rate of charge of current

and $\frac{di}{dt}$ tries to assume an infinite value at the time of switching, the voltage builds up to the point where arcing occurs. Generally, the arcing is oscillatory, due to the underdamped nature of the load, with energy storage in both inductive and capacitive elements.

Other types of tools which generate electrical noise are those which use switch contacts for changing operational modes, starting, running, etc. When electrical contacts make or break, the operation may not be a "clean" opening or closing, and some contact "bounce" may occur. Often the bounce may cause inadvertent opening and closing through ten or more on-off cycles occurring in rapid sequence. The "bounce" on-off cycles become somewhat random, with both the period of closure and the period between closures being variable.

In the case of brushes and commutators, the switching action is also somewhat irregular due to the mechanisms of arcing and extinguishing of arcing. Changing air currents vary in the arc extinguishing pattern.

Considering the arcing and contact bounce irregularities and the wide variety of loads which may be switched, it can be seen that electrical noise can have an extremely wide range of spectral and time characteristics. Thus, the problem of designing a test which can cover all possible conditions becomes a formidable task. The problem is compounded by the fact that any noise generated by a tool will be

conducted into the electric power network. All pairs of wires within the network become transmission lines having terminations which do not provide impedance matching. Therefore, reflections can build on these lines. Furthermore, when many tools are used in the same vicinity, the synergistic effects may result in much higher switching noise levels, with peak levels being a function of tool usage patterns.

In designing a switching noise simulator, test techniques used by other agencies were first studied. Two basic types of noise generators were found; one type used a chattering relay to switch various loads onto the GFCI; the other used a "showering arc" system in which switching was accomplished by a spark gap driven by a high-voltage transformer and associated circuitry. After reviewing the various test techniques, CERL selected an approach that used a chattering relay in which the closure rate could be controlled externally by either repetitive or random sources. The random closure provided flat spectral density of the generated noise. Filling of the spectrum could be varied by the type of load applied to the GFCI by the relay contacts.

Since the number of GFCIs to be tested was so large, there was not enough time to subject each to a variety of loads. Therefore, most GFCIs were tested by using the chattering relay to switch a resistive load corresponding to full load onto the GFCI. This resistive load was made up from eight high-power resistors in series. Each resistor had 0.8 ohms resistance, was 2 in. (5 cm) in diameter and 14 in. (35 cm) long, and was made from a nichrome band wound in a single-layer solenoid. Thus, the resistor bank had considerable inductance. In addition to the resistive load, a 200-W isolation transformer and an electric floor heater with a fan and heating elements were used as loads for some tests.

Contact bounce wave forms from the relay are shown in Figures B2 and B3. The two waveforms show that there is considerable variation in closure periods and open periods. If many oscilloscope waveforms are observed, it becomes evident that the contact bounce is highly random, thus insuring spectral flatness of the noise signal generated.

Test Procedures

Tests performed on the GFCIs consisted of connecting the selected load to the GFCI load contacts through the chattering relay contacts. While subjected to this load, the GFCI was monitored for malfunctioning and tripping, and the trip threshold was measured three times with the fault simulator. Figure B4 summarizes data derived in this test.

Vibration

Test Approach

Portable generators are often required to produce emergency lighting

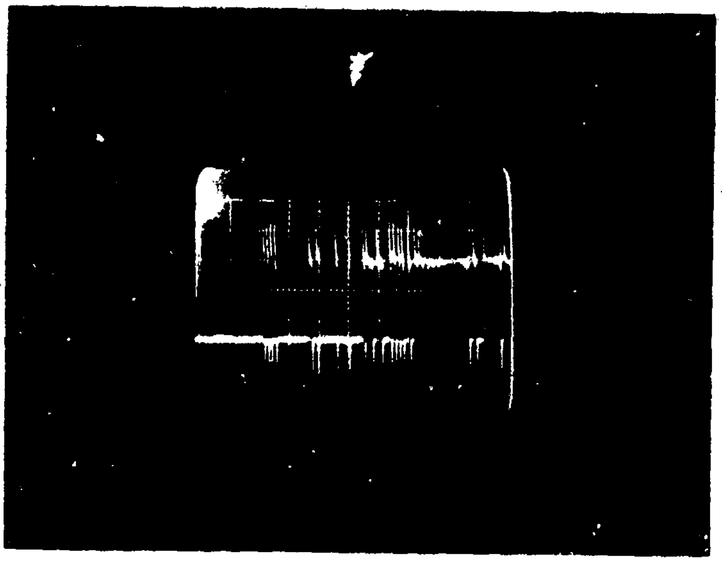

Figure B2. Relay contact bounce waveform (first trial).

Figure B3. Relay contact bounce waveform (second trial).

Manufacturers	Type: C. Bkt	Type: Recep.	Version	Threshold Current	Effect of Switched Resistive Load: Failure	Effect of Switched Resistive Load: Increased Threshold	Effect of Switched Resistive Load: Decreased Threshold	Effect of Switched Transformer Load: Increased Threshold	Effect of Switched Transformer Load: Decreased Threshold	Effect of Switched Transformer Load: Trips
American #R1	x		R	5.19 mA			5.12 mA		4.35 mA	
American #R2 (failed before this test)	x		R							
American #R3 (failed during this test)	x		R		x					
American #R4	x		R	4.81 mA			4.67 mA		4.46 mA	
American #R5	x		R	5.26 mA			4.98 mA		0.00 mA	x
American #R6	x		R	5.20 mA			5.00 mA		4.53 mA	
AMF Paragon #R1		x	R	5.12 mA			No change 5.12 mA	5.15 mA		
AMF Paragon #R2		x	R	5.08 mA			5.07 mA		4.00 mA	
AMF Paragon #R3		x	R	5.33 mA			5.28 mA	5.37 mA		
AMF Paragon #R4		x	R	5.30 mA		5.36 mA			4.23 mA	
AMF Paragon #R5		x	R	4.97 mA			4.96 mA		3.43 mA	
AMF Paragon #R6		x	R	5.25 mA			5.20 mA		4.03 mA	

Figure B4. Summary cf chattering relay test data.

Manufacturers	Type: C. Bkt	Type: Recep.	Version	Threshold Current	Effect of Switched Resistive Load: Failure	Effect of Switched Resistive Load: Increased Threshold	Effect of Switched Resistive Load: Decreased Threshold	Effect of Switched Transformer Load: Increased Threshold	Effect of Switched Transformer Load: Decreased Threshold	Effect of Switched Transformer Load: Trips
Bryant #2	x		R	5.42 mA			No change 5.42 mA		5.02 mA	
Bryant #3	x		R	5.46 mA		5.50 mA			5.36 mA	
Bryant #5	x		R	5.46 mA		5.49 mA			5.28 mA	
Bryant #6	x		R	5.52 mA			5.26 mA		5.19 mA	
Cutler Hammer #R1	x		R	4.89 mA		4.95 mA			3.50 mA	
Cutler Hammer #R2	x		R	4.90 mA		4.95 mA			3.19 mA	
Cutler Hammer #R3	x		R	4.76 mA		4.84 mA			3.19 mA	
Cutler Hammer #R4	x		R	5.19 mA		5.25 mA			3.82 mA	
Cutler Hammer #R5	x		R	4.97 mA			No change 4.97 mA		3.91 mA	
Cutler Hammer #R6	x		R	5.22 mA		5.25 mA			4.39 mA	

Figure B4 (cont'd)

Manufacturers	Type: C. Bkt	Type: Recep.	Version	Threshold Current	Effect of Switched Resistive Load: Failure	Effect of Switched Resistive Load: Increased Threshold	Effect of Switched Resistive Load: Decreased Threshold	Effect of Switched Transformer Load: Increased Threshold	Effect of Switched Transformer Load: Decreased Threshold	Effect of Switched Transformer Load: Trips
Federal Pacific #R1	x		R	5.69 mA			No change 5.69 mA		5.35 mA	
Federal Pacific #R2	x		R	5.77 mA		5.79 mA			5.32 mA	
Federal Pacific #R3	x		R	5.34 mA			5.32 mA		4.65 mA	
Federal Pacific #R4	x		R	5.27 mA			5.24 mA		4.18 mA	
Federal Pacific #R5	x		R	5.51 mA		5.52 mA			4.18 mA	
Federal Pacific #R6	x		R	4.90 mA		4.97 mA			3.83 mA	
General Electric #R1	x		R	5.35 mA		5.50 mA		5.37 mA		
General Electric #R2	x		R	5.15 mA		5.27 mA			5.14 mA	
General Electric #R3	x		R	5.37 mA		5.47 mA			5.34 mA	
General Electric #R4	x		R	5.17 mA		5.32 mA			No change 5.17 mA	
General Electric #R5	x		R	5.30 mA		5.39 mA			5.21 mA	
General Electric #R6	x		R	5.27 mA		5.40 mA			5.14 mA	

Figure B4 (cont'd)

Manufacturers	Type: C. Bkt	Type: Recep.	Version	Threshold Current	Effect of Switched Resistive Load: Failure	Effect of Switched Resistive Load: Increased Threshold	Effect of Switched Resistive Load: Decreased Threshold	Effect of Switched Transformer Load: Increased Threshold	Effect of Switched Transformer Load: Decreased Threshold	Effect of Switched Transformer Load: Trips
General Electric #R1	x		R	5.25 mA		5.36 mA			5.21 mA	
General Electric #R2	x		R	5.10 mA			5.04 mA		5.04 mA	
General Electric #R3	x		R	4.88 mA		5.03 mA			4.53 mA	
General Electric #R5	x		R	5.24 mA		5.26 mA			0.00 mA	
Hubbell Spider #1				4.97 mA		5.15 mA		5.09 mA		
Hubbell Spider #2				5.00 mA		5.11 mA		5.08 mA		
Hubbell Spider #3				4.89 mA		5.03 mA		5.02 mA		
Hubbell Spider #4				4.92 mA		5.04 mA		4.93 mA		
Hubbell Spider #5				4.90 mA		4.97 mA			4.82 mA	
Hubbell Spider #6				5.32 mA		5.40 mA		5.44 mA		
Hubbell Yellowbox				3.74 mA			3.67 mA		0.00 mA	

Figure B4 (cont'd)

Manufacturers	Type C. Bkt	Type Recep.	Version	Threshold Current	Effect of Switched Resistive Load Failure	Effect of Switched Resistive Load Increased Threshold	Effect of Switched Resistive Load Decreased Threshold	Effect of Switched Transformer Load Increased Threshold	Effect of Switched Transformer Load Decreased Threshold	Effect of Switched Transformer Load Trips
ITE #R1	x		R	5.66 mA			5.35 mA		5.14 mA	
ITE #R2	x		R	5.58 mA		5.66 mA			5.30 mA	
ITE #R3	x		R	5.76 mA			4.45 mA		4.68 mA	
ITE #R4	x		R	5.5[illegible]			5.24 mA		4.98 mA	
ITE #R5	x		R	5.75 mA			5.63 mA		5.72 mA	
ITE #R6	x		R	5.07 mA			4.92 mA		4.77 mA	
Leviton #R1		x	R	5.06 mA			5.05 mA		5.02 mA	
Leviton #R2		x	R	4.80 mA			4.78 mA		4.75 mA	
Leviton #R3		x	R	5.36 mA		5.40 mA			5.25 mA	
Leviton #R4		x	R	5.22 mA			5.20 mA		5.10 mA	
Leviton #R6		x	R	4.88 mA		4.89 mA		4.89 mA		

Figure B4 (cont'd)

Manufacturers	Type		Version	Threshold Current	Effect of Switched Resistive Load			Effect of Switched Transformer Load		
	C. Bkt	Recep.			Failure	Increased Threshold	Decreased Threshold	Increased Threshold	Decreased Threshold	Trips
3M #R1		x	R	4.97 mA		5.05 mA			4.96 mA	
3M #R3		x	R	4.55 mA		4.70 mA		4.58 mA		
3M #R4		x	R	4.70 mA		4.87 mA		4.72 mA		
3M #R6		x	R	4.80 mA		4.82 mA			4.78 mA	
Pass & Seymour #R1		x	R	5.23 mA		5.45 mA			4.39 mA	
Pass & Seymour #R2		x	R	4.26 mA			4.22 mA	4.28 mA		
Pass & Seymour #R3		x	R	5.11 mA			5.04 mA		4.86 mA	
Pass & Seymour #R4		x	R	5.19 mA		5.40 mA			4.73 mA	
Pass & Seymour #R5		x	R	5.59 mA		5.81 mA			4.51 mA	
Pass & Seymour #R6		x	R	4.50 mA		4.60 mA			0.00 mA	

Figure B4 (cont'd)

Manufacturers	Type		Version	Threshold Current	Effect of Switched Resistive Load			Effect of Switched Transformer Load		
	C. Bkt	Recep.			Failure	Increased Threshold	Decreased Threshold	Increased Threshold	Decreased Threshold	Trips
Square D #R1	x		R	5.14 mA			4.92 mA		4.88 mA	
Square D #R2	x		R	5.55 mA			5.42 mA		4.95 mA	
Square D #R3	x		R	5.10 mA			5.04 mA		0.00 mA	x
Square D #R4	x		R	5.13 mA			4.98 mA		4.92 mA	
Square D #R5	x		R	5.22 mA			5.21 mA		4.65 mA	
Square D #R6	x		R	5.30 mA			5.27 mA		5.09 mA	
Square D #R1		x	R	4.93 mA		5.03 mA		4.99 mA		
Square D #R2		x	R	4.79 mA		4.94 mA			4.59 mA	
Square D #R3		x	R	5.24 mA		5.28 mA			4.93 mA	
Square D #R4		x	R	4.77 mA		4.89 mA			4.68 mA	
Square D #R5		x	R	5.03 mA		5.24 mA			4.41 mA	
Square D #R6		x	R	4.98 mA		5.15 mA			4.97 mA	

Figure B4 (cont'd)

and temporary power on construction sites. The National Electric Code Article 210-20 requires that GFCIs be used on portable generators lower than 5 kW and on all those that are grounded.

When so used, the GFCI is usually mounted directly on the generator set, and is thus subjected to vibrations from the engine and generator. Generally, no vibration isolators are used, and the GFCI can be subjected to high vibrational acceleration levels. Field usage of GFCIs on portable generators has caused some problem--for example, at the New Melones Dam in California.

In determining vibration acceleration (G) levels to which the GFCIs were to be exposed, several military standards were reviewed. MIL-STD-810C--Environmental Test Methods--lists a test for instruments mounted to aircraft engines. Since it was anticipated that the small engines would produce similar G forces, this standard was chosen as a guide for testing GFCIs.

The test described in this section was conducted to investigate the effect of vibrations to which GFCIs used at construction sites might be subjected.

Procedure

The GFCIs were mounted one at a time on the vibrator, and power was applied. The sweep generator provided a test frequency sweep from 50 Hz to 2 kHz in 5 min. The cycle automatically repeated for a total test time of 1 hour. The objective was an average acceleration of 20 G, with peaks limited to 40 G. A typical frequency vs. G acceleration actual curve is provided in Figure B5. Two breaker type and receptacle type GFCIs of each manufacturer were tested. A 2.5 mA current fault was present on each GFCI during tests. GFCI trips vs. acceleration forces were recorded.

Hot/Cold Environment

Test Approach

Since GFCIs on construction sites must be capable of operating in temperature extremes, hot and cold environmental tests were included in the program. A low point of 20°F (-6°C) and high of 130°F (54°C) were selected as test points, since this was the range of the available environmental chamber and because this temperature range would cover most GFCI uses.

Procedure

The GFCIs were connected to the threshold tester and placed in the environmental test chamber. The temperature was allowed to stabilize at the low test point and data were read and recorded. This method was continued until all GFCIs had been tested at the 20°F (-6°C) temperature.

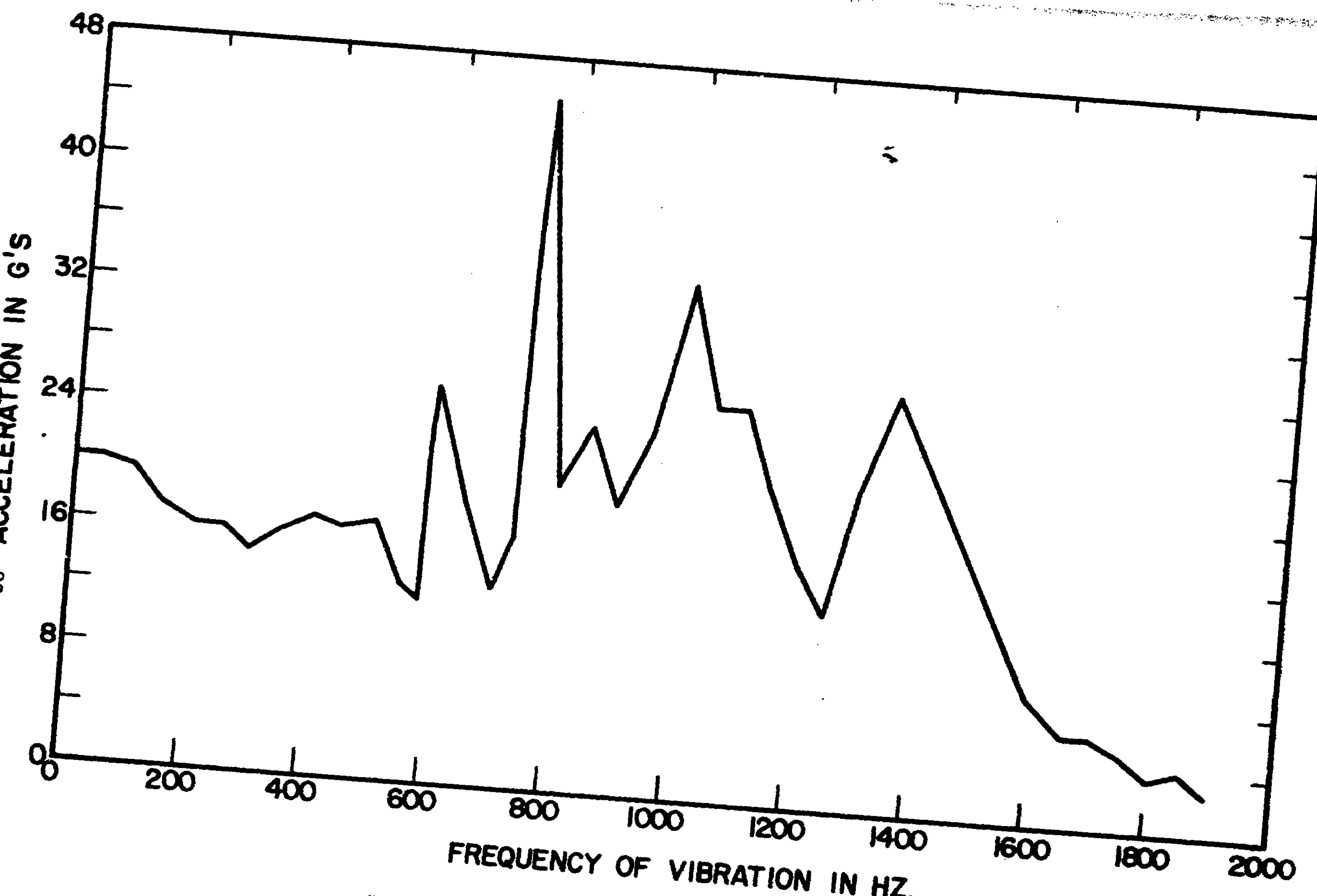

Figure B5. Frequency vs. Acceleration data.

The temperature was then elevated to 130°F (54°C), and the procedure was repeated.

Figure B6 is a typical example of data acquired during the testing.

Condensation

Test Approach

Seventy percent of the field sites surveyed reported moisture as a serious problem in operating GFCIs. The problems were considered to be connected mainly with items external to the GFCIs, such as the cords, connectors, tools, etc.

Underwriters Laboratory, Inc. has conducted leakage current and water resistivity measurements on plugs, connectors, and electrical cords. Their results indicated little leakage in new electrical cords and slightly more in the cords where part of the jacket had been removed or split. The largest leakage currents, which were measured in the connection of plugs and connectors, approached readings of 300 mA when the connections were submerged in the water, with a resistivity of approximately 300 ohms/cm. (See Appendix D for complete Underwriters Laboratory report.)

No know, test of severity applicable to construction sites has been performed on the effect of condensation on the GFCI. The tests described in this section were conducted solely to determine the effect of high humidity and condensation on the GFCIs.

Procedure

Two GFCIs from each manufacturer were mounted in duplex receptacle boxes or in their respective load center panels. All covers were left open for maximum penetration of moisture, and the devices were mounted on the inside wall of a 5 x 5 x 10 ft (1.5 x 1.5 x 3 m) enclosed steel box. A humidifier was placed inside the box and left operating during the entire 26 days that the GFCIs were undergoing tests.

Before the condensation test was begun, two each of breaker and receptacle types for each manufacturer were subjected to high humidity conditions with power applied continually. It was theorized that the heat produced by the GFCI electronics might be enough to keep moisture out; however, this was not confirmed by further testing.

Since the GFCI is sometimes used as an on-off switch at actual construction sites, and is left in the off position during nonduty hours, the "worst case" condition (power off) was chosen for the test program.

Trip threshold value vs. the number of days that GFCIs were tested is plotted in Figures B7-B13.

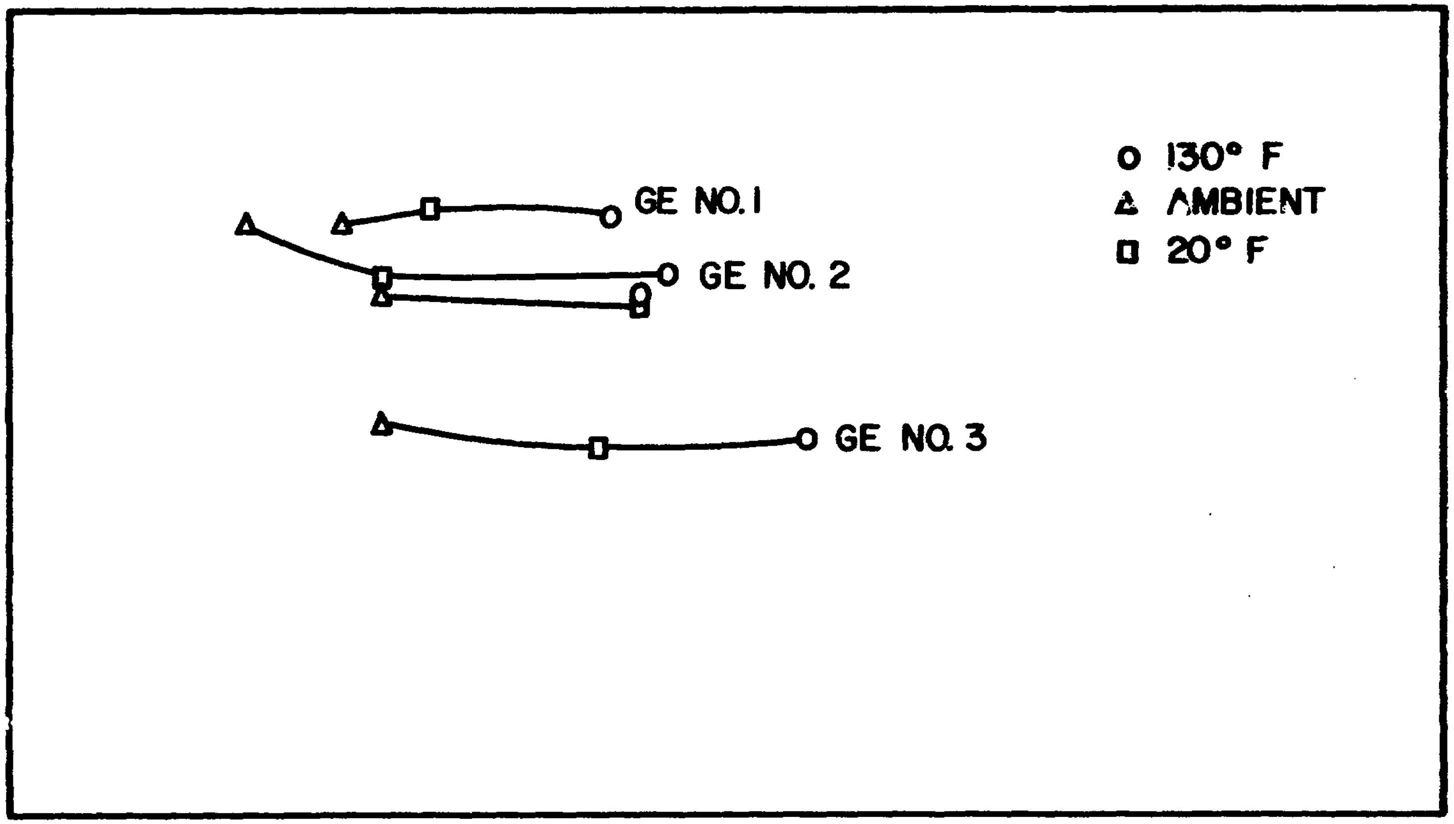

Figure B6. Hot and cold environmental data.

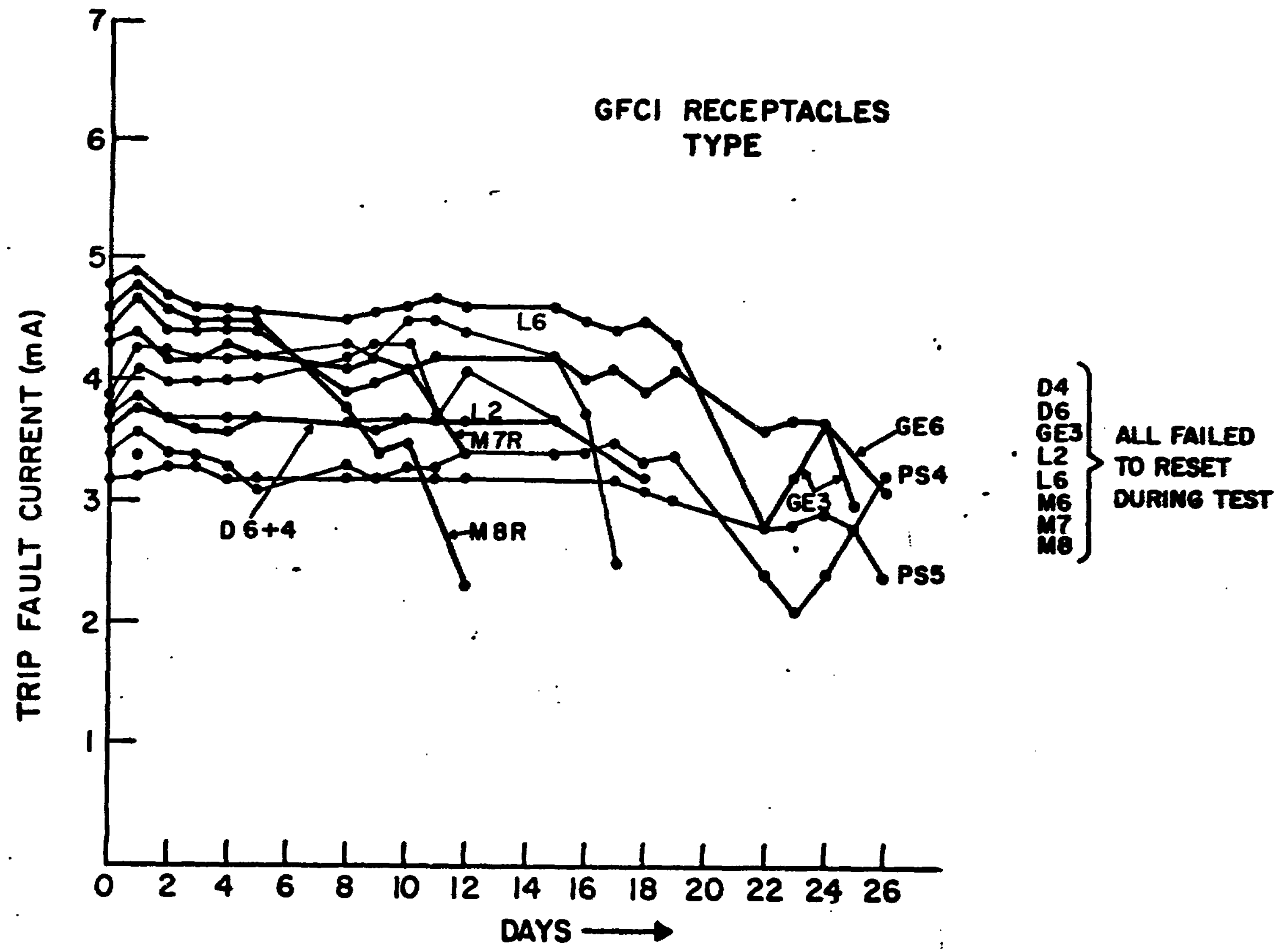

Figure B7. Condensation data (receptacles).

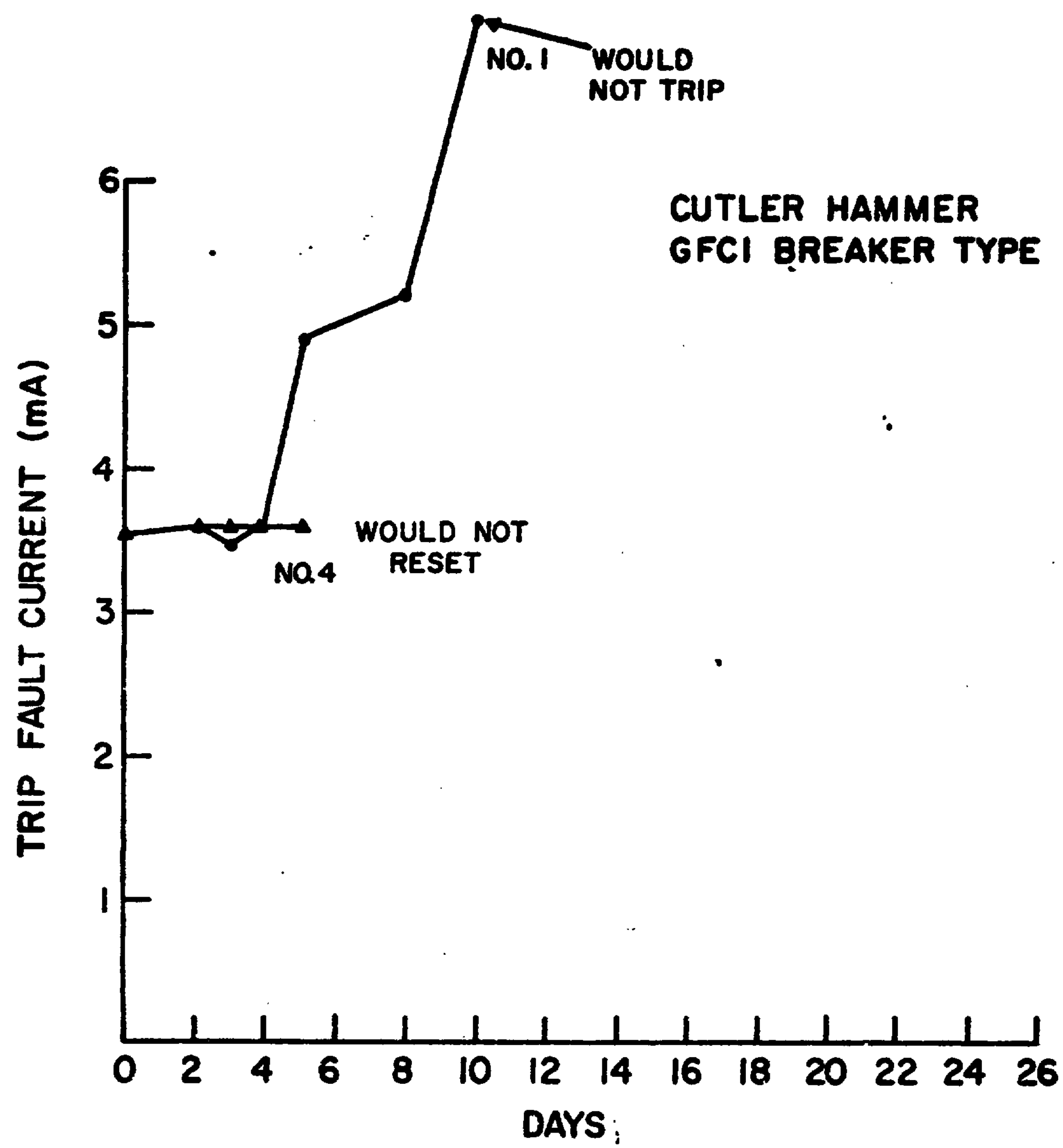

Figure B8. Condensation data (Cutler Hammer).

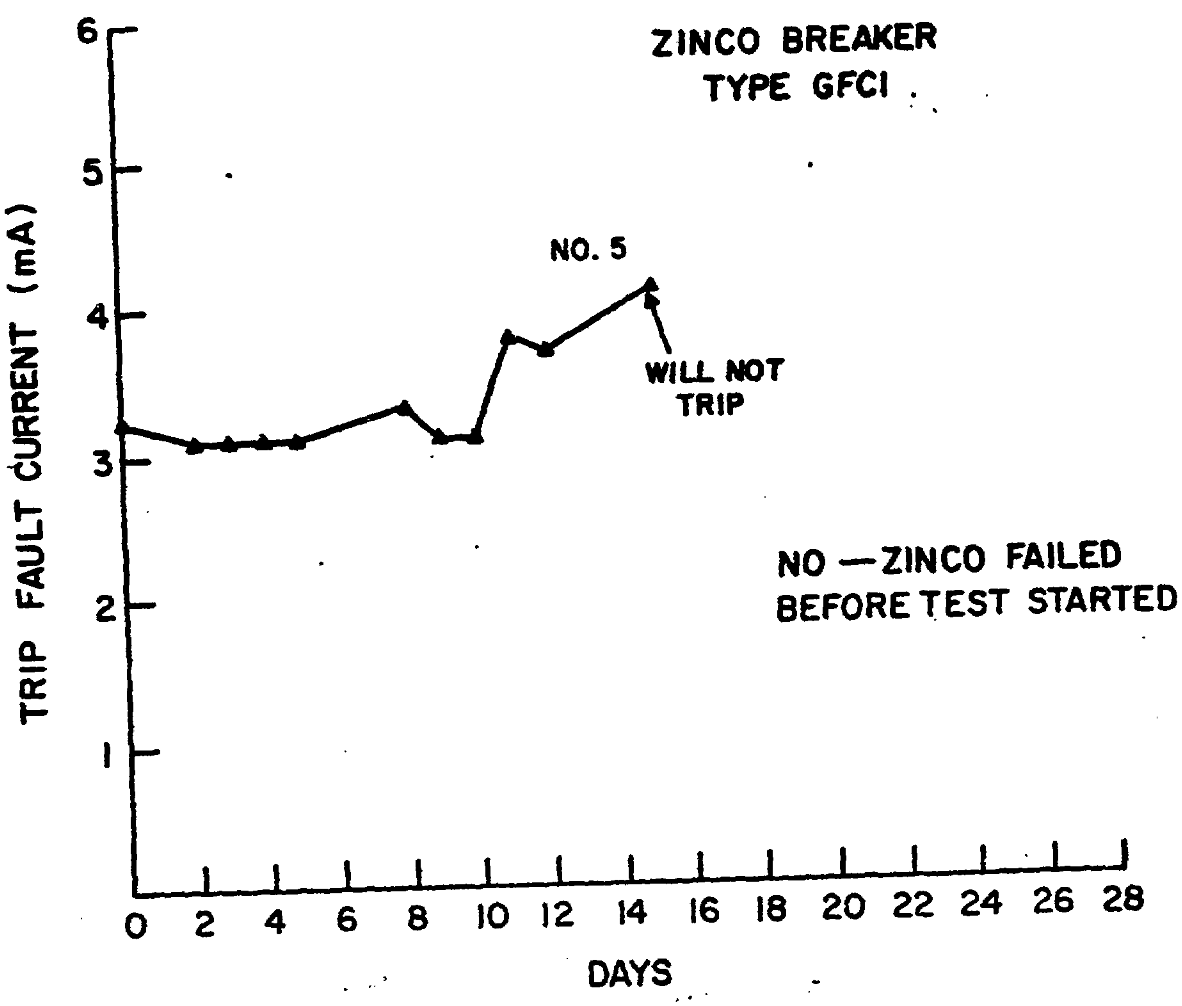

Figure B9. Condensation data (Zinco breaker).

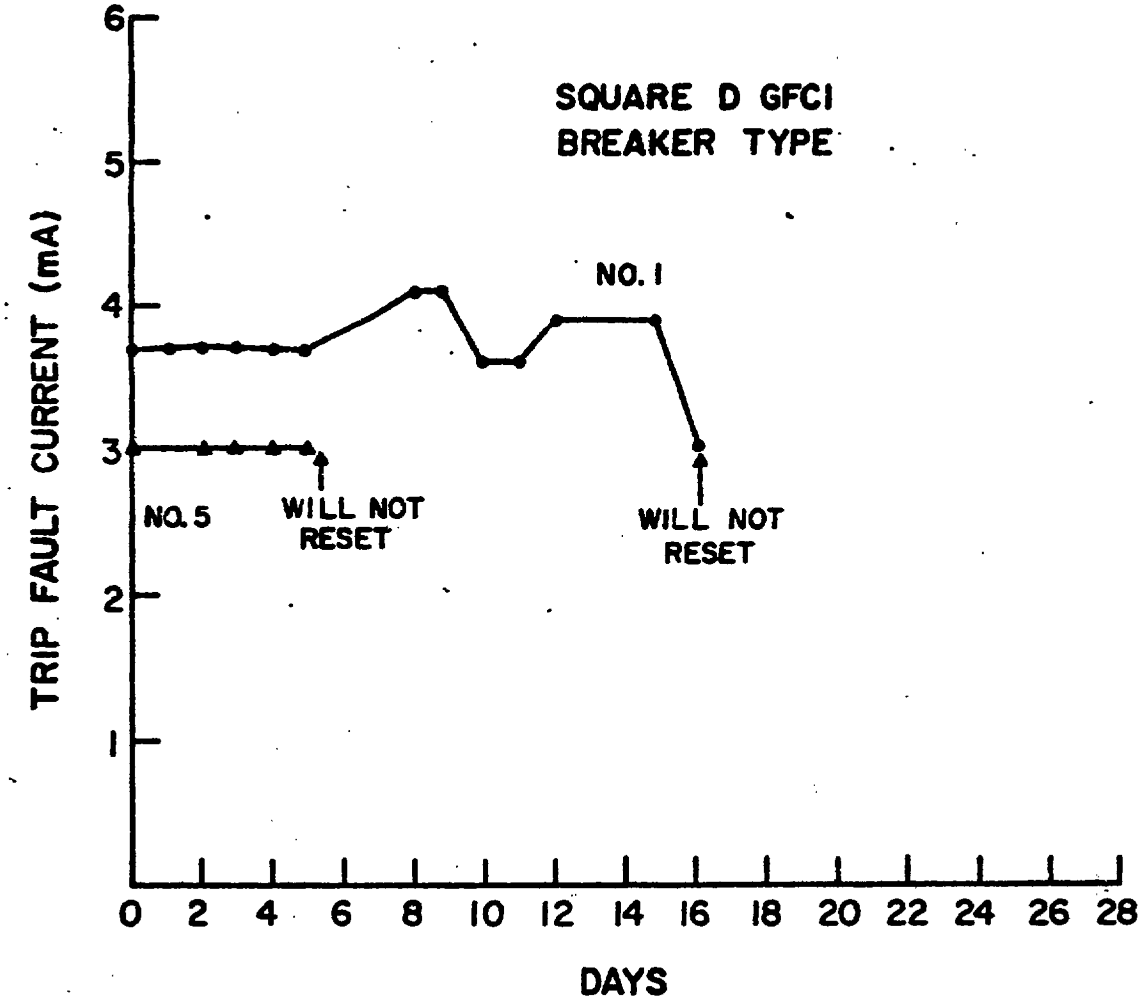

Figure B10. Condensation data (Square D breaker).

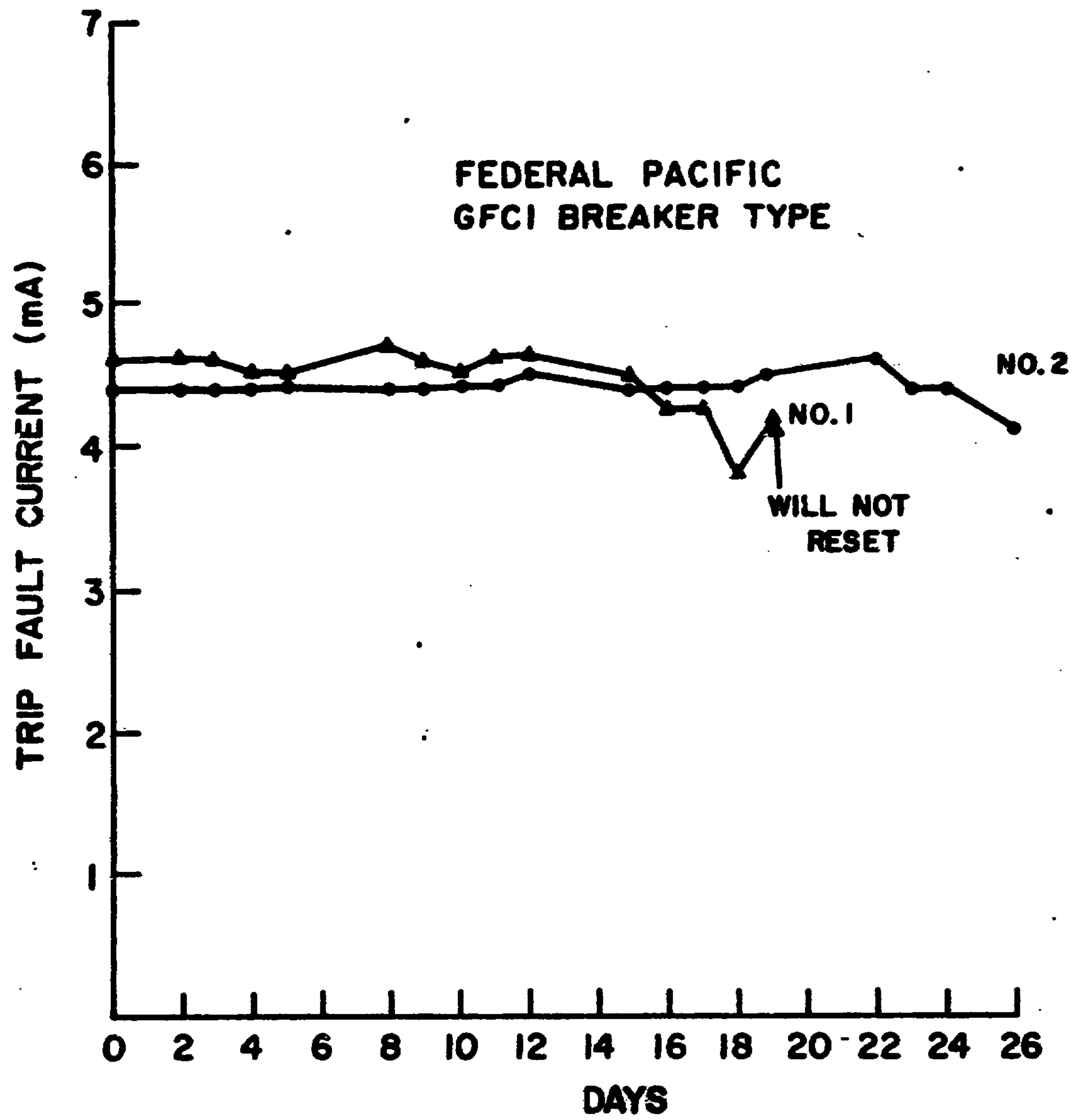

Figure B11. Condensation data (Federal Pacific breaker).

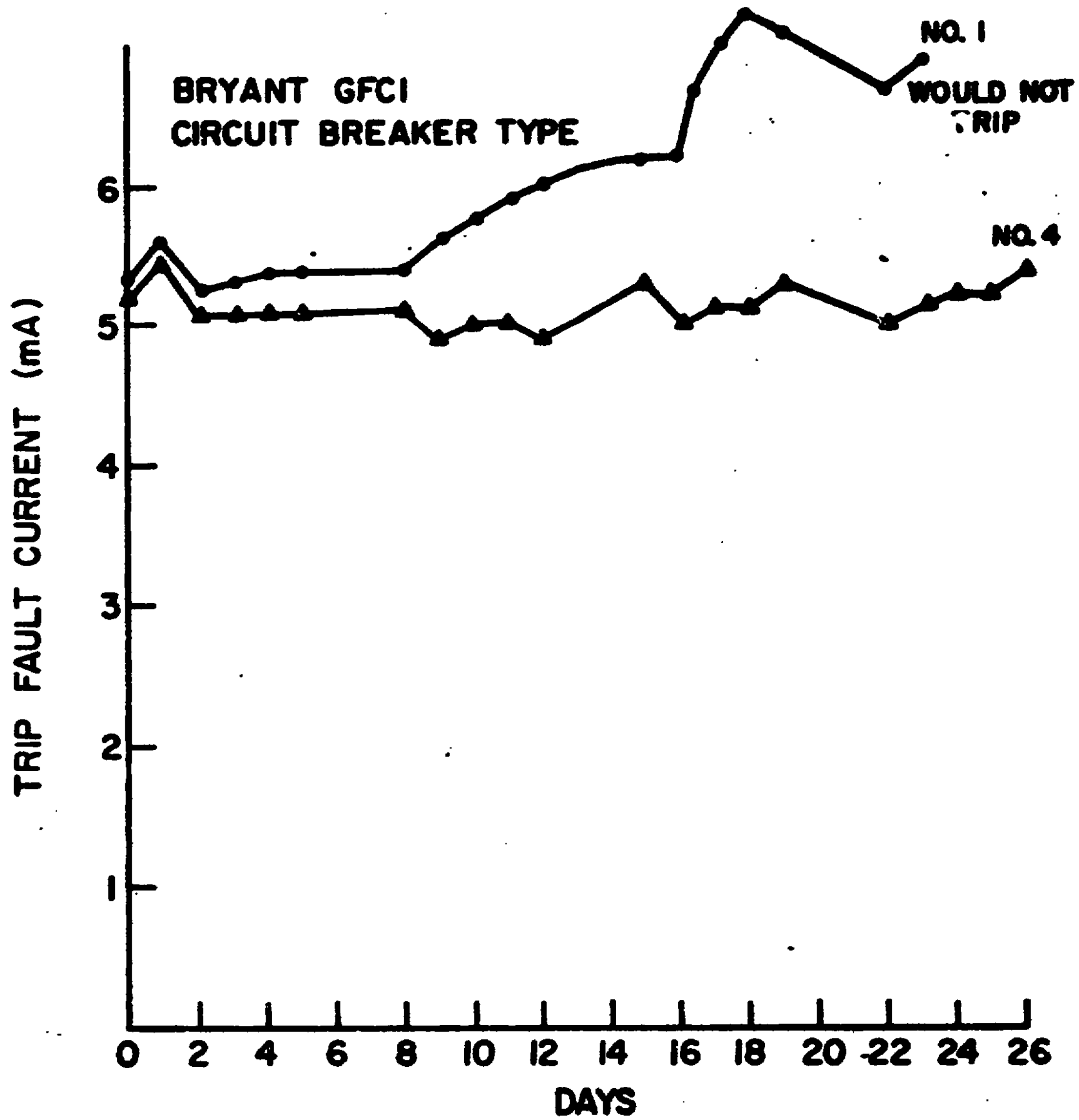

Figure B12. Condensation data (breaker) (Bryant).

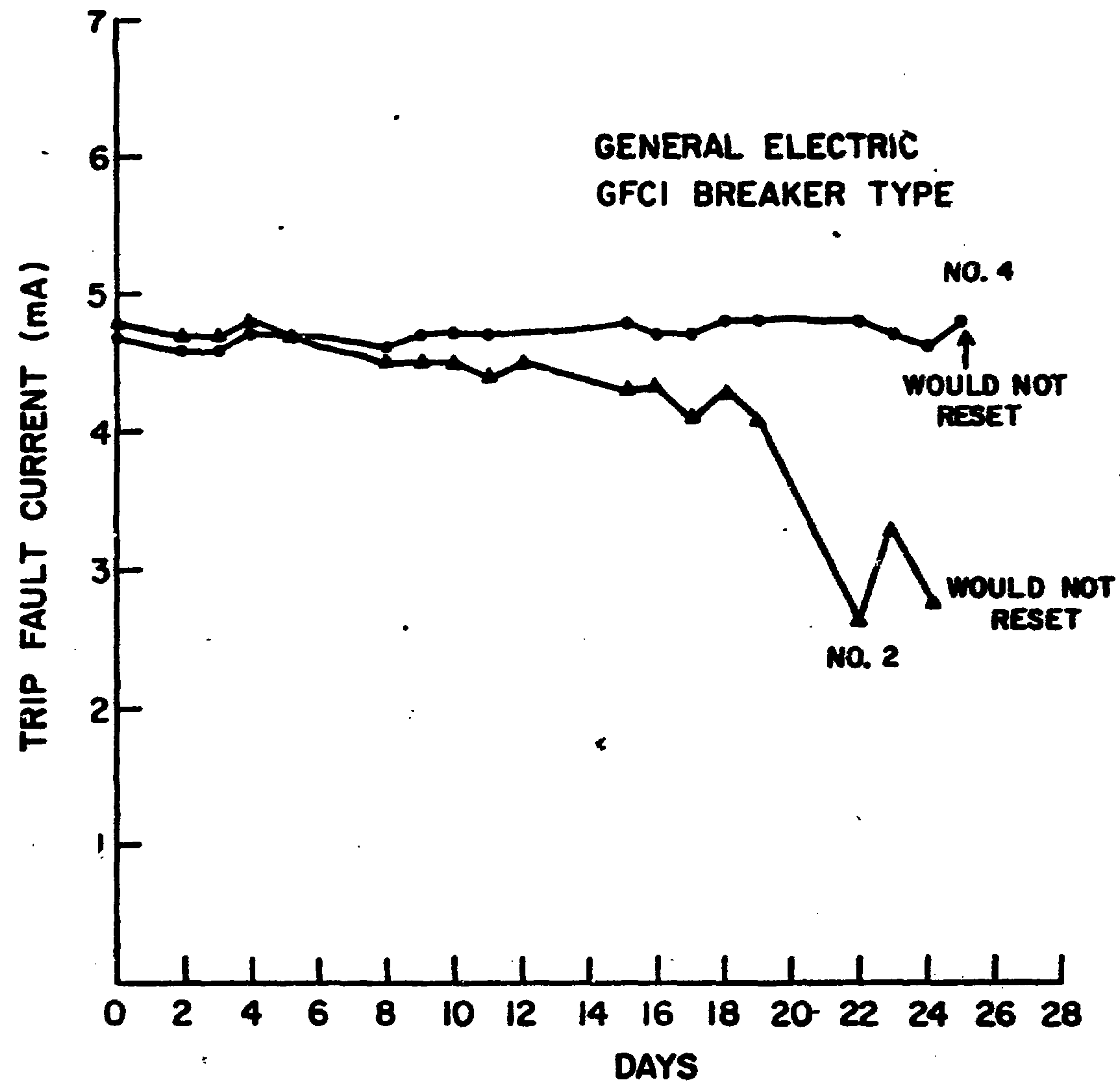

Figure B13. Condensation data (breaker) (General Electric).

APPENDIX C
NATIONAL BUREAU OF STANDARDS
INVESTIGATION OF GROUND FAULT CIRCUIT INTERRUPTERS

Survey of Ground Fault Circuit Interrupter Usage for Protection Against Hazardous Shock

Robert W. Beausoliel and William J. Meese

The ground fault circuit interrupter (GFCI) is increasingly becoming an integral part of building electrical systems to protect human life. Building researchers, designers, and contractors should have a working knowledge of their purpose and operational characteristics. This report describes the functional principles of GFCIs and relates their performance to effects of electric current on the human body. Information concerning the history, research and testing, installation practices, fire protection aspects, types, manufacturers and costs of GFCIs are included. The trend of requiring installation of GFCIs on more and more electrical circuits by regulatory authorities for safety purposes is outlined. Controversies concerning feasibility, reliability, nuisance tripping and other problems are discussed; laboratory and field investigations addressing these problems should be undertaken.

Permanent installations of GFCIs are being made in new residential and other construction, but very few are being installed in older buildings. The rationale for this needs to be examined. Because of higher leakage currents probable in most older construction, GFCIs manufactured under present standards may not be feasible in older buildings.

Key words: Branch circuit protection; electric shock; electrical safety; ground fault; leakage current; prevention of electrocution.

1. Introduction

The ground fault circuit interrupter (GFCI) is a device designed to open an electric circuit when a ground fault current exceeds a certain value. Underwriters' Laboratories Standard 943 [1][1] defines ground fault as "denotes an unintentional electrical path between a part operating normally at some potential to ground, and ground." The National Electrical Code (NEC) [2] defines ground fault circuit interrupter as "a device whose function is to interrupt the electric circuit to the load when a fault current to ground exceeds some predetermined value that is less than that required to operate the overcurrent protective device of the supply current." Section 4 of this report contains a description of the functional principles of GFCIs.

In the U.S.A. most GFCIs are designed to operate when current to ground exceeds 5 milliamperes (mA). GFCIs will not function to protect against line-to-line faults. Fuses or circuit breakers are required for this purpose. However, on most branch circuits, fuses or circuit breakers will not operate until currents exceed 15 or 20 amperes (A), which is far above safe currents through the body.

The need for a comprehensive report concerning ground fault circuit interrupters (GFCIs) became apparent during a preliminary investigation by the National Bureau of Standards on the evaluation of the possible use of flat conductor cable (FCC) in buildings. This investigation of FCC is being done for the U.S. Department of Housing and Urban Development.

[1] Figures in brackets indicate literature references at the end of this publication.

1.1. Flat Conductor Cable in Buildings

Development of flat conductor cable (FCC) has been primarily for aerospace applications. In recent years, however, as a part of its technology "spinoff" program, the National Aeronautics and Space Administration (NASA) has proceeded with a program to adapt FCC for use in electrical and communication circuits in buildings [3].

The geometry of FCC is such that more area of its conducting path is exposed to potential contact by people, either directly or via metal building components, than is the case with conventional cable with round conductors. Surface mounting of FCC, which may provide economies in building construction, increases the possibility of such contact. The primary proposed means of protection against shock hazards of FCC electrical circuits is with ground fault circuit interrupters (GFCIs) [3]. While other means of protection, such as covering with grounded metal sheets, may be feasible, a study of GFCIs became apparent as a prerequisite to the evaluation of FCC.

1.2. Scope

This report describes and analyzes the use of GFCIs in buildings. The performance required of GFCIs is related to the effect of electric shock on the human body. Other means of protecting against electric shock are discussed. Protection by GFCIs against some, but not all, electrically caused fires is discussed. Information is included concerning the history, research and testing, foreign experience, installation practices, manufacturers, types, and costs of GFCIs.

Up to the present time, only round electrical conductors have been used in building wiring except in a ~~few minor prototype installations~~ of FCC. This report on the survey of GFCI usage assumes the use of conventional electrical cables with round conductors unless otherwise stated.

2. Shock Hazards to the Human Body

Generally, except for certain industrial or other special applications, buildings in the United States are equipped with nominal 120 and 240 V, 60 Hz, single phase electrical branch circuits. Both 120 and 240 V circuits have 120 V with respect to earth and building grounds. Figure 1 describes a typical residential electrical service.

The potential for shock exists when a person makes contact between conductors at different potentials or between a conductor and ground. Referring to Figure 1 this may occur when a person gets across:

(a) A black or red wire and a white (neutral) wire;
(b) A black or red wire and ground;
(c) A black and a red wire or;
(d) A white (neutral) wire and ground. (This last case is usually not hazardous because the difference in potential between neutral wires and ground is usually small.)

2.1. Line-to-Ground Shocks

When a person completes a circuit between a voltage source and ground, a current may flow through the body. In most electrical circuits this current path would be an abnormal path. In this case a GFCI on the circuit could remove the voltage quickly, preventing death or serious injury to the victim. See functional description of GFCI, Section 4.

2.2. Line-to-Line Shocks

Protection against shock (current through the body) primarily depends on the design of electrical systems and equipment, including circuit outlets. Adequate electrical insulation and enclosures should prevent inadvertent contact with current carrying elements. However, proper caution must be observed as it is difficult to protect a person who contacts two conductors which are at different potentials and both of which are intended to carry current under normal circumstances. In this case a GFCI would not operate.

2.3. Currents in the Human Body

The magnitude of the current that may flow through the body is determined by the potential difference or voltage of the circuit, body resistance and other resistances in series with the body. A person's skin provides much of the body resistance. The resistance of human skin varies with individuals. When dry it may be as much as 100000 to 300000 ohms/cm^2, but when the skin is wet, or broken by a cut, the resistance may be only one percent of this value [4].

A value of 500 ohms is commonly considered to be the minimum resistance of the human body between hands or between other major extremities of the body such as hand and foot. A resistance of 500 ohms is frequently used in estimating shock currents during

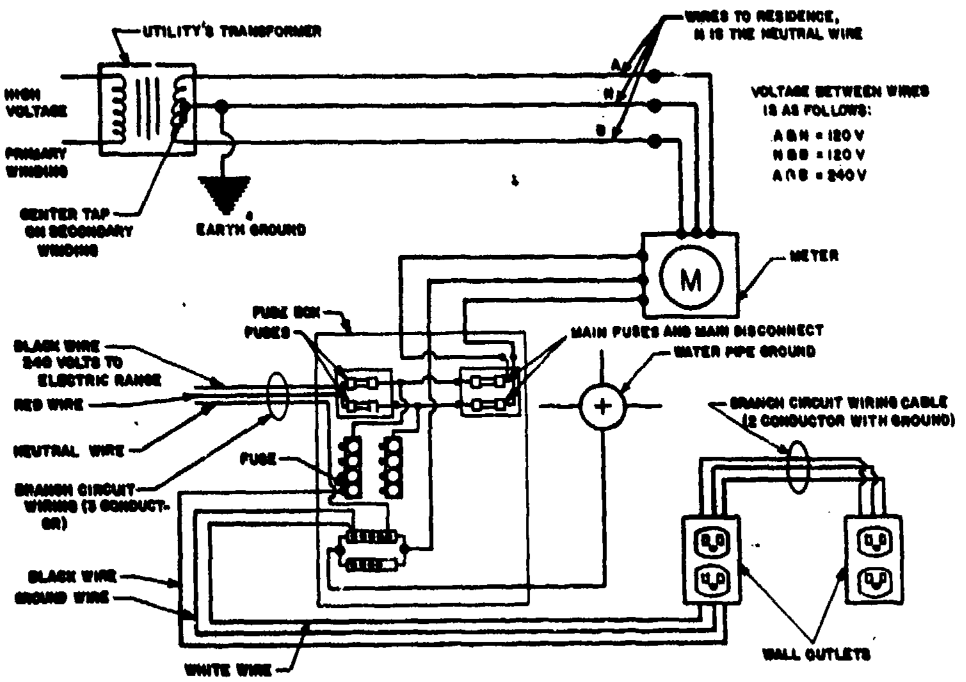

FIGURE 1. *Typical residential electrical service.*

industrial accidents [4]. A current of 240 mA would flow between hand and foot assuming a 500 ohm resistance and 120 V potential (see Figure 2). Usually, in the case of electric shock involving nominal 120 V circuits, the current in the body is much less than 240 mA. The effects of various levels of current on the human body are described below.

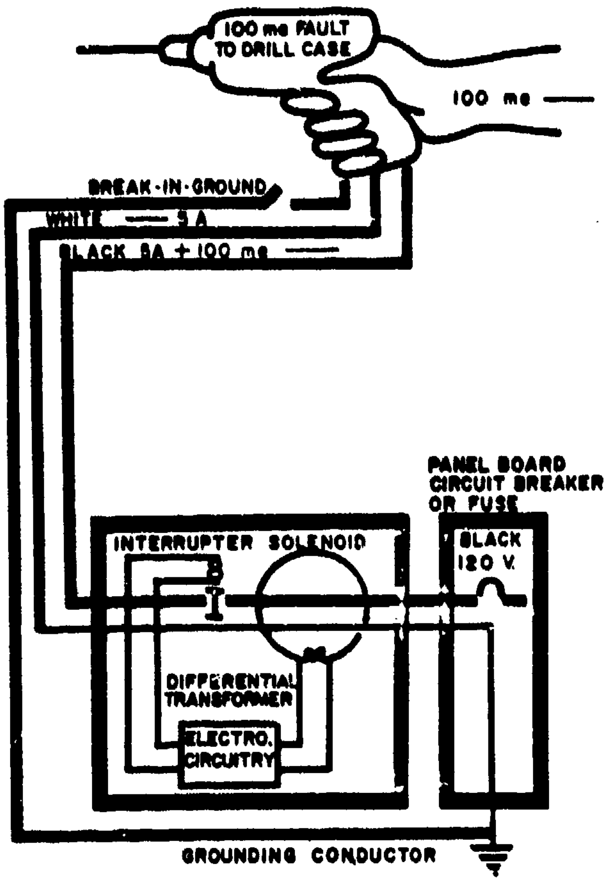

FIGURE 2. *Illustration of GFCI operation.*

GFCI detects a fault current (assumed to be 100 mA) and opens circuit. Fault current is passing through person who feels shock until circuit is opened. Note: Without a break in the ground path, current would pass through grounding conductor and GFCI would open the circuit. In this case a person would probably not feel a shock.

2.3.1. Perception Currents

Depending upon body resistance and applied voltage, the shock victim is subjected to a particular current level. The level at which alternating current stimulates the nerves is indicated by a slight tingling sensation and is known as the perception current. The mean perception current value for men is 1.1 mA at 60 HZ and the mean value for women is 0.7 mA [4]. (RMS values are used in this paper)

2.3.2. Reaction Currents

Currents equal to or slightly greater than perception currents could produce an involuntary reaction resulting in an accident. Such a current is known as the reaction current.

2.3.3. Let-go Currents

Except for the startling effect and involuntary movement which may result in an accident, the smallest electric shock of importance is the current which causes a loss of voluntary control of the hand when grasping an electrified object [5]. When the current is increased there comes a time when the victim cannot let go of the conductor; the victim is said to "freeze" to the circuit. The maximum current a person can endure and still release the conductor by using muscles directly stimulated by the current is called his "let-go" current [4]. The following observation concerning let-go experiments conducted over a 25-year period are given by Dalziel [4]:

1. An individual's let-go current is essentially constant if sufficient time is allowed for recovery between shocks.
2. An individual can endure, with no adverse effects, repeated exposure to the reactions associated with currents of his let-go level.
3. The physiological reactions resulting in the inability of let-go are essentially the same over the limited frequency range 50 to 60 Hz.

The maximum uninterrupted reasonably safe let-go currents are 9 mA for normal men and 6 mA for normal women. It has not been possible to obtain reliable values of let-go currents for children [4].

2.3.4. Currents at or Slightly Above "Let-go" Levels

Currents at or a little above those at which a person can "let-go" of a circuit, but below currents causing ventricular fibrillation (see Section 2.3.5) may contract chest muscles and stop breathing during the period of the shock [4], [6]. Normal breathing may resume when the current is interrupted. However, with prolonged current collapse, asphyxia, unconciousness, and even death may occur in a matter of minutes.

2.3.5. Currents Causing Ventricular Fibrillation

Larger currents may produce an effect on the heart that is medically known as ventricular fibrillation. Dalziel states that "from a pratical point of view, this term means stoppage of heart action and blood circulation." The human heart rarely recovers spontaneously from fibrillation [4].

Ventricular fibrillation experiments cannot be conducted on man. The only recourse is to experiment on animals and extrapolate animal data to man [4]. Such data has been obtained by Kouwenhoven and others [7]. It is believed that ventricular fibrillation in

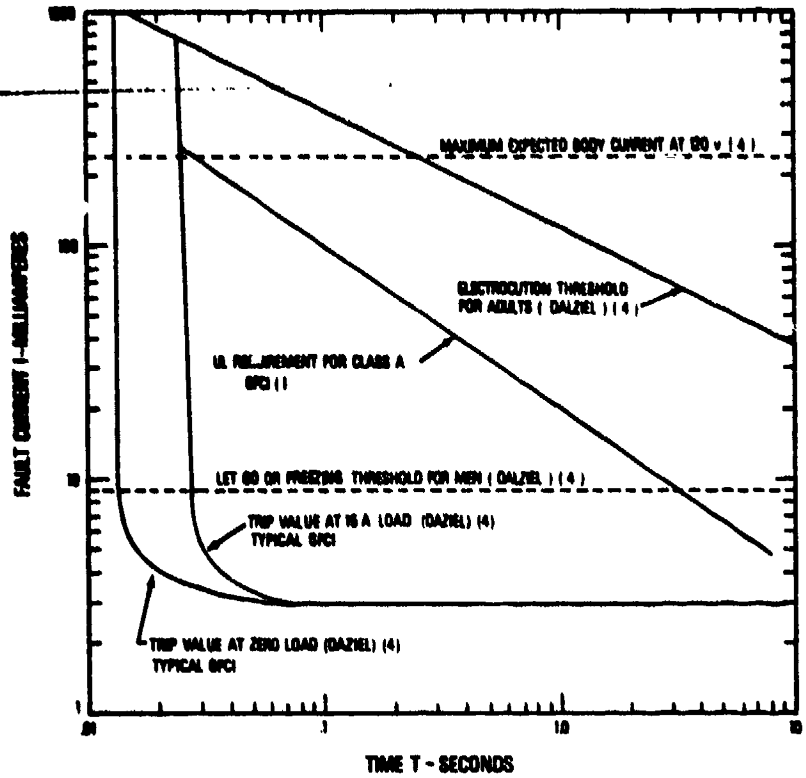

FIGURE 3. *Characteristic elements—GFCI performance.*

normal adult workers is unlikely if shock intensity is less than $116/T^{1/2}$ mA, where T is in seconds, as given by Dalziel. See electrocution threshold curve in Figure 3.

The shorter the exposure time to a given current the less the energy that is experienced by the victim [6]. Figure 3 shows the threshold relationship between currents and time which may result in electrocution (ventricular fibrillation) at 120 V, 60 Hz. Note that values indicating the "let-go" threshold current and the current when the body resistance is at the anticipated minimum of 500 ohms are shown in this figure.

2.3.6. Effects at Higher Currents

Currents greater than those which result in ventricular fibrillation may cause cardiac arrest, respiratory inhibition, irreversible damage to the nervous system, serious burns and unconsciousness. No numerical data are available for currents which cause these effects [4].

2.4. Frequency Aspects

Perception currents and let-go currents increase considerably as frequency is increased. Relatively little is known concerning the effect of frequency on fibrillation currents. However, studies show that the current required to produce fibrillation in dogs at 3000 Hz is 22–28 times that at 60 Hz [4].

3. Means to Protect Against Shock Hazards

Eight means are known for reducing the hazard of electric shock [4]. These eight means are described below.

3.1. Isolation

Nationally recognized codes define "isolated" and "isolation by elevation" as follows:

"Isolated means that an object is not readily accessible to persons unless special means for access are used." [2] [8].
"Isolation by Elevation means elevated sufficiently so that persons may safely walk underneath." [8].

Elevating electric circuits to isolate them is common practice for overhead transmission and distribution lines. Isolation of electric circuits in buildings is not common except in some industrial and other special purpose buildings.

3.2. Isolation Transformers

Isolation transformers are used to protect against shock hazards primarily in medical equipment. [4] In Europe, however, they have been used on bathroom circuits [9]. Safety is achieved because the secondary of the transformer serving the load is ungrounded and is isolated from the primary windings which are connected to the building supply. This isolation should prevent hazardous line-to-ground shocks.

3.3. High Frequency/Direct Current

With high frequency alternating current (see Section 2.4) or with direct current, it has been demonstrated that people or animals are less vulnerable to electric shock [4]. High frequency/direct current have principally been used as a means to protect against electric shock in applications in the medical field.

3.4. Guarding

Nationally recognized codes define "guarded" as follows:

"Guarded means covered, shielded, fenced, enclosed, or otherwise protected by means of suitable covers or casings, barrier rails or screens, mats or platforms, to remove the liability of dangerous contact or approach by persons or objects to a point of danger. [2] [8].

"Note: Wires which are insulated, but not otherwise protected, are not considered as guarded." [8].

Most interior wiring which is a permanent part of a building is guarded. The wiring to many portable lamps and appliances is insulated but not guarded.

3.5. Insulating

Nationally recognized codes define "insulated" and "insulating" as follows:

"Insulated means separated from other conducting surfaces by a dielectric substance or air space permanently offering a high resistance to the passage of current and to disruptive discharge through the substance or space.

"Note: When any object is said to be insulated, it is understood to be insulated in a suitable manner for the conditions to which it is subjected. Otherwise, it is within the purpose of these rules uninsulated. Insulating covering of conductors is one means for making the conductors insultated." [8]

"Insulating (where applied to the covering of a conductor, or to clothing, guards, rods, and other safety devices) means that a device, when interposed between a person and current-carrying parts, protects the person making use of it against electric shock from the current-carrying parts with which the device is intended to be used; the opposite of conducting." [8].

3.6. Double Insulation

Double insulation denotes a term which applies to a system of insulating electrical equipment which is superior to and less likely to fail in service than more usual methods of insulating. The National Electrical Code (NEC), Article 250–45 (c), does not require grounding of some portable tools and appliances protected by a system of double insulation [2]. Although double insulation has had a good record, it may not be safe under certain circumstances. Dalziel states that double insulated electric shavers have caused two or three electrocutions. The accidents happened when the victim dropped the shaver into a water-filled toilet bowl or wash basin and immediately reached for it without first disconnecting the plug [4].

3.7. Grounding

Nationally recognized codes define "grounded" and "effectively grounded" as follows:

"Grounded means connected to earth or to some extended conducting body which serves in place of the earth." [2]

"Effectively Grounded means permanently connected to earth through a ground connection or connections of sufficiently low impedence and having sufficient current-carrying capacity to prevent the building up of voltages which may result in undue hazard to connected equipment or to persons." [8].

Grounding requirements in Codes apply to both circuits ("system grounds") and to conducting materials enclosing electric conductors or equipment ("equipment grounds"). The National Electrical Code [2] states that the purposes of grounding are:

"Circuits are grounded to limit excessive voltages from lightning, line surges or unintentional contact with higher voltage lines and to limit the voltage to ground during normal operation.

"Conductive materials enclosing electric conductors or equipment, or forming part of such equipment, are grounded for the purpose of preventing a voltage above ground on these materials.

"Circuits and enclosures are grounded to facilitate overcurrent device operation in case of insulation failure or ground faults."

The National Electrical Code recommends grounding of nonelectrical equipment through the following statement. "Where extensive metal in or on buildings may become energized and is subject to personal contact, adequate bonding and grounding will provide additional safety." The Code requires that both electrical and exposed non-electrical metal parts of mobile homes which may become energized be effectively bonded and grounded to the grounding terminal or enclosure of the distribution panelboard.

A position paper prepared by an Ad-hoc Task Force on Grounding for the National Commission on Product Safety pointed out both advantages and disadvantages in the practice of grounding appliances and electrical systems [10]. This paper encouraged the installation of GFCIs on circuits supplying 15 and 20 A outlets. With properly adjusted and maintained GFCIs, the safety of cord-connected appliance usage does not generally depend on the grounding of the accessible metal parts of the appliance [10].

Practically all residences in the United States that use electricity are properly grounded (in accordance with applicable Codes) at the service entrance point. While grounding in residences has many advantages, some disadvantages are briefly summarized below:

(1) By having electrical systems grounded, anyone in contact with the ground and touching a live part will receive a shock [10].

(2) Equipment grounding increases the area of possible contact and locations at which persons can establish electrical contact with the earth. This can increase the chance of shock because of more probable simultaneous contact with a grounded object when there is accidental contact with an intended live part.

(3) If an untrained or inexperienced user repairs the supply cord of a grounded appliance, he may make improper connections that can cause the exterior metal parts to be connected to the live conductor instead of the grounding conductor. In this case the casing of the appliance may have a potential of 120 volts to ground. The referenced report states that experience has shown that this is a real problem in the usage of three-wire grounding cords and plugs [10].

Connecting the ground wire to the wrong terminal in replacing or repairing a plug resulted in 21 electrocutions among 88 investigated in Australia [11]. While most recently built homes are equipped with grounding-type receptacles, only about 15 percent of American homes constructed prior to 1970 had power receptacles built to accept the plug with a grounding prong. Users may install an adapter which connects the grounding prong to a screw on the receptacle plate to update non-grounding type receptacles. Even when the adapter is used, however, the screw, plate, and receptacles themselves may not be grounded [11]. One survey of hospitals showed 55 to 100 plugs had the grounding prong clipped off and the ground wire was broken in 30 out of 45 adapter plugs inspected [11]. An Underwriters' Laboratories study found that only 13 percent of the power tools in use in the United States were properly grounded. [11]

3.8. Shock Limitation

Ground fault circuit interrupters limit the duration and energy of a shock. Section 4 describes the functional principles of these innovative devices.

4. Functional Description of GFCIs

The functional description of a typical GFCI is shown in Figure 2. As long as the current flowing in the black wire equals the current flowing in the white wire, the voltage in the secondary winding of the differential transformer is zero. If current above the trip value of the GFCI flows to ground, such as shown in Figure 2, the solid state electronic circuitry causes the interrupter solenoid to disconnect the circuit. Energy to operate GFCIs is supplied by the building branch circuits.

4.1. Functional Characteristics

The functional characteristics of Group 1, Class A, GFCIs (see Section 8) are described in this report. The principle difference between Class A and Class B GFCIs is the higher trip value (20 mA) permitted for Class B.

A Group 1, Class A GFCI has a trip value of 5 mA or less. A GFCI does not limit the current to ground to 5 mA or some other value, but opens the circuit whenever its trip value is exceeded.

The upper value of line-to-ground current that a person will experience on ordinary 120 or 240 V branch circuits is approximately 240 mA assuming that his resistance is 500 ohms (See section 2.3). A person would probably feel the shock of this current before the GFCI opened the circuit. However, a GFCI is designed to trip fast enough (about 25 milliseconds or less at 240 mA) to prevent electrocution. See plot of a GFCI characteristics (trip time versus fault current) in Figure 3.

UL requires that a Class A GFCI be capable of interrupting the electric circuit to the load when the fault current to ground is within the range of 5 to 264 mA in accordance with the following relationship: [1]

$$T = \left(\frac{20}{I} \right)^{1.43}$$

where T is in seconds and I is the fault current to ground in milliamperes. Figure 3 shows a plot of this equation which can be compared with the curves showing the electrocution threshold for adults, the let-go threshold and maximum expected body currents on ordinary branch circuits. Analysis of available

data (on animals and adult humans) by Underwriters' Laboratories indicated that protection against electrocution for man, including a 2-year old child should be provided if all combinations of body current and duration are below the plot of the above equation [12].

GFCIs will not function to protect the circuit against line-to-line overloads. A fuse or circuit breaker is required for this purpose. On most branch circuits, however, a fuse or circuit breaker will not open a circuit until current exceeds 15 or 20 A, which, of course, is far above maximum expected currents through the body.

4.2. Test Circuits

GFCIs are required by Underwriters' Laboratories to have a means whereby they can be readily tested at any time to determine if they will function if there is a ground fault [1]. Figure 4 illustrates a supervisory circuit or test circuit. This circuit produces a ground fault with a current slightly above the GFCIs trip value (approximately 6–7 mA for a 5 mA GFCI) within the GFCI when the test button is pressed.

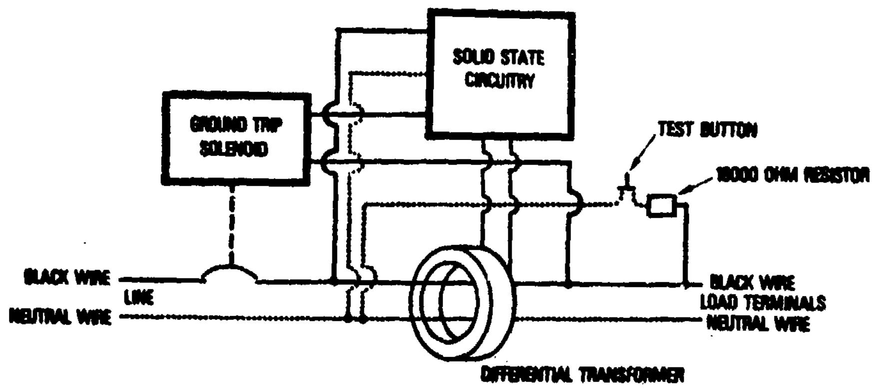

FIGURE 4. *A GFCI supervisory circuit.*

5. Protection Against Fire

Ground fault circuit interrupters are principally used for protection against shock hazards. However, they can provide protection against some fire hazards. Fires which might start where overheating is occurring between a line conductor and ground or where there is arcing between a line conductor and ground may be prevented by the fast action of ground fault circuit interrupters.

GFCIs will not open a circuit when overheating is occurring along the current path until a ground fault occurs. Glowing electrical connections have been established and sustained for many hours in the laboratory without tripping ground fault circuit interrupters [13]. On the other hand, if overheating from such connections causes deterioration of insulation, permitting a line conductor to contact a grounded object, the GFCI will readily trip.

6. History of GFCIs

Devices that interrupt an electric circuit when the ground fault current exceeds a predetermined value (which is less than that required to operate the overcurrent devices, e.g. fuses, circuit breakers) have been known for many years. Such devices have been used to protect high-voltage power lines since the 1920s. They were set to operate at 10 to 20 percent of the maximum operating current or trip value of the circuit overcurrent devices [6]. For example a power circuit breaker having an overload trip value of 200 A was set up to trip on ground faults of only 20 to 40 A, which was considered a great achievement of the day [6].

Some 10 years later the importance of protecting against low-voltage "burndowns" in industrial equipment was recognized in Germany. Subsequently, Germany developed devices having a line-to-ground-trip value of about 500 mA to protect industrial equipment [6]. About 15 years ago, the French and the Austrians developed two-wire earth-leakage circuit breakers having a trip value of 25 to 30 mA [6]. In Europe a GFCI device is called an earth-leakage circuit breaker. The French-Austrian innovation was followed in the U.S.A. in 1962 by the development of the transistorized GFCI having a ground-current trip value of 5 mA. This means that the circuit breaker will trip with a 5- mA line-to-ground fault current. The 5 mA trip level is now required by the Underwriters' Laboratories Inc., and by the Canadian Standard Association for most GFCI applications [6].

7. GFCI Regulatory Provisions

Required use of GFCIs by regulatory authorities is increasing. Generally, provisions, requiring the installation of GFCIs are first incorporated in the National Electrical Code [2] before becoming part of State, local or other regulations.

7.1. National Electrical Code

The trend toward increased use of GFCIs is illustrated by comparing GFCI requirements in the last three editions (1968, 1971 and 1975) of the National Electrical Code (NEC) [14, 15, 2]. The NEC is developed under procedures of the National Fire Protection Association and the American National Standards Institute and is a voluntary standard as published. However, because of adoption, (sometimes with revisions) by State and local authorities, the installation of electrical equipment in buildings throughout the U.S.A. is generally in accordance with the NEC.

The 1968 edition of the NEC [14] was the first edition to mention GFCIs. It recommended that attachment plug receptacles in the area adjacent to swimming pools be installed on a circuit protected by a ground fault circuit interrupter. The 1971 Edition of the NEC [15] required that receptacles located between 10 and 15 feet from the inside wall of a swimming pool be protected by a GFCI. It prohibited outdoor receptacles closer than ten feet from a pool. The 1971 edition permitted the use of GFCIs as one means of protecting against fault conditions involving underwater lighting fixtures which might result in electrical shock hazards. Also, the 1971 NEC edition required that all electrical equipment used with storable swimming pools be supplied with circuits protected by GFCIs. The use of GFCIs in boatyards and marinas on receptacles used to provide shore power for boats was suggested.

Quite widespread use of GFCIs was required by the 1971 NEC on dates subsequent to the effective date of the Code. In residential occupancies all 120V, single phase, 15 and 20 A receptacle outlets installed outdoors on or after January 1, 1973 were required to have approved GFCI protection for personnel. Such protection could be provided on branch circuits or on feeders supplying applicable branch circuits. The use of GFCIs was suggested for other circuits, in other locations and in other occupancies. All 15 and 20 ampere receptacle outlets on single phase circuits for construction sites were required to have GFCI protection for personnel on or after January 1, 1974.

For residential occupancies, (including mobile homes and mobile home parks) in addition to receptacle outlets on outdoor circuits, the 1975 NEC [2] requires that 120 V, single phase, 15- and 20-A receptacle outlets in bathrooms have GFCI protection for personnel. For construction sites, GFCI protection is required except when receptacle outlets on permanent wiring are used or when power is supplied by 5 kW or smaller portable generators meeting certain requirements.

Branch circuits supplying under-water lighting fixtures in swimming pools which operate at more than 15 V are required by the 1975 NEC to have GFCI protection. Also, GFCI protection is required on branch circuits supplying fountain equipment operating at more than 15 V. In general, other 1975 NEC requirements pertaining to swimming pool GFCI protection are similar to those in the 1971 NEC. However, the 1971 NEC suggested use of GFCIs in boatyards and marinas was eliminated from the 1975 Code. "Leakage currents inherent in boats" was the apparent reason for this reversal in the trend to recommend and require greater use of GFCIs each time the NEC is up-dated.

7.2. Occupational Safety and Health Administration

The Occupational Safety and Health Adminstraton (OSHA) of the US Department of Labor is responsible for issuing and enforcing regulations concerning the safety of workers in places of employment. On July 1, 1974 OSHA, pending reconsideration of the requirement, postponed enforcement of the National Electrical Code provision requiring GFCIs on all 15 and 20 ampere receptacle outlets on single phase circuits for construction sites [16].

7.3. Other Authorities

In building and construction many authorities issue regulations, specifications or other requirements. For example the Oak Ridge National Laboratory requires GFCIs on outdoor receptacles within 15 feet of the inside walls of reactor pools [17]. To determine requirements pertaining to the use of GFCIs, the authority having jurisdiction should be consulted.

8. Ground Fault Equipment in USA

The Underwriters' Laboratories recognize two types of ground fault equipment.

(a) The first type is ground fault sensing and relaying equipment. This equipment is designed to open conductors at predetermined values of ground-fault current not exceeding 1200 A [18]. This equipment has peripheral interest to the purposes of this report.

(b) The second type is a GFCI which functions to open a nominal 120 V to ground branch circuit when there is a fault current to ground exceeding some predetermined value. This fault current is far less than that necessary to trip a circuit breaker or "blow" a fuse.

8.1. Groups of GFCIs

UL recognizes two groups of GFCIs [19]:

(a) Group I GFCIs are to be used only on circuits which have grounding conductors. There is some disagreement with this requirement regarding "older" installations which do not have equipment ground provisions [20]. Group I GFCIs are covered by UL Standard No. 943 [1].

(b) Group II GFCIs are to be used only on circuits that do not have grounding conductors. [19] They are intended for use with isolation transformers. No UL standard exists for Group II GFCIs. They are not used in residential and commercial buildings and have no other general use. Therefore, Group II GFCIs are not considered further in this report.

8.2. Classes of Group I GFCIs

There are two classes of Group I GFCIs: [19]

(a) Group I, Class A GFCIs may be used with most utilization equipment. However, swimming pool circuits installed prior to local adoption of the 1965 edition of the National Electrical Code are likely to exhibit sufficient leakage current to cause a Class A GFCI to trip. A Class A GFCI must trip when the current to ground exceeds 5 mA. The required maximum trip time depends on the fault current, as shown in figure 2.

(b) Group I, Class B GFCIs are restricted for use with under-water swimming pool lighting fixtures, provided also that the fixture is not marked to specify the use of a Class A GFCI. Class B GFCIs must trip when the current to ground exceeds 20 milliamperes.

The primary purpose of the 20 mA rating is for practicable reasons, that is to allow for the greater leakage current to ground inherent in underwater lighting systems of some of the older swimming pools. Class B GFCIs have far less use than class A GFCIs. Recent underwater lighting systems have improved leakage current characteristics.

9. Manufacturers and Costs of GFCIs

Five manufacturers have produced GFCIs with UL listings as of June 1974. [19]. The GFCIs produced by these manufacturers must be in compliance with UL Standard 943 [1].

The list price for duplex receptacle type GFCIs and for single circuit breaker, plug-in type GFCIs for panelboard installation may be $40 to $50 or more; the price to contractors is usually less. The cost of portable cord-connected GFCIs is usually more than twice the cost of permanently installed GFCIs.

10. Installation of GFCIs

GFCIs are installed in three configurations as follows: [21]

(a) They may be located in the breaker panelboard and may be an integral part of the circuit breaker.

(b) They may be located in cord-connected form for portable and temporary operation.

(c) They may be located in standard duplex receptacle form. There are two forms of this GFCI. A feed through type protects itself and other receptacles and devices connected to it on the load side. The second type, a "dead-end" type, protects only itself and any connected load.

10.1. UL Installation Requirements

UL requires the following installation requirements to "minimize" false tripping: [19]

A Class A device may not be connected: [1]
(a) To swimming-pool equipment installed prior to adoption of the 1965 National Electrical Code. [22]
(b) To longer lengths of load conductor than indictated in Table 32.1 of UL Standard 943.

A Class B device may: [1]
(a) Only be used with underwater swimming pool lighting fixtures but not with such fixtures that are marked for use with a Class A GFCI.
(b) Not be connected to longer lengths of load conductor than indicated in Table 32.1 of UL Standard 943.

10.2. Single Sensors

Conductors (except equipment ground) for a circuit should pass through a single sensor; these conductors cannot be "shared" by any other circuit. [20] For example, sometimes the neutral conductors for more than one branch circuit are combined in a junction box. This technique cannot be used where a GFCI is involved because this connection results in parallel return neutral paths for each of the branch circuits, involved, resulting in an imbalance in the GFCI sensor. [20]

10.3. Leakage Current Problems

In January 1969, the American National Standards Institute published a standard for leakage current for appliances [23]. The standard limits leakage currents for portable cord connected 120V appliances to 0.5 mA and to 0.75 mA for stationary or fixed appliances. Underwriters' Laboratories Standard 943 [1] defines "leakage current" as "denotes all currents including

capacitively coupled currents which may be conveyed between energized parts of a circuit and (1) ground or (2) other parts."

Leakage current of appliances has been reduced over the years. Some older appliances were manufactured with leakage current limits of 5 mA and some of these may still be in use [6]. In such cases, if GFCIs trip at about 5 mA, the sum of normal wiring leakage and likely leakage of appliances may result in GFCIs tripping even though an electrical fault per se does not exist.

Leakage currents in older houses and older buildings present practical problems, which need investigation. See section 12, Foreign Experience. Older houses may present more of a shock hazard than new buildings, but the present thrust is for building officials to ignore existing electrical installations. The National Electrical Code [2] requirements are not retroactive. Enforcing authorities are not, to any noticeable extent, attempting to require GFCIs in existing buildings. However, excessive leakage currents of permanent branch circuit wiring when added to the leakage currents of appliances or other utilization equipment may make the use of 5 mA GFCIs impractical.

10.4. Inductive Circuit Problems

False trippings have occurred where there were high voltage spikes during the opening of inductive circuits with relays, contactors and similar equipment. This problem is said to be solved by the addition of a capacitor of proper size to limit the voltage to a level which a GFCI can withstand. It is stated that these problems are solved on an individual basis by variation in relay and other inductive device design [20].

10.5. Loss of Lighting Problems

One authority suggests that GFCIs should be used with circuits supplying only wall and floor receptacles rather than ceiling or wall-bracket illuminating fixtures [6]. This would preclude the loss of lights when GFCIs operate. The rationale for this is that the electric shock hazard is associated to a greater degree with portable appliances than with ceiling or wall-bracketed illuminating fixtures.

11. GFCI Testing and Research

As is the case with many safety devices, GFCIs only operate when something is wrong. To assume that a GFCI will operate when there is a fault to ground but not give false operations is an important aspect of its technology.

11.1. UL Tests

Group I GFCIs are subjected to extensive tests by the Underwriters' Laboratories in accordance with their standard No. 943 [1]. GFCIs which meet this standard are "listed" by UL. UL uses the term "list" and not the term "approve" regarding products they consider to be satisfactory. As a private organization UL does not have authority to approve products. Enforcing authorities; usually State, local or Federal governmental agencies, approve products installed in buildings. However, listing of electrical products by UL often becomes tantamount to approval by enforcing authorities.

Test and other evaluations of GFCIs by UL cover the following: [1]

(a) Resistance to corrosion
(b) Rainproof enclosures
(c) Grounding
(d) Frame and enclosure
(e) Provision for wiring system
(f) Insulation
(g) Accessibility to energized parts
(h) Internal wiring
(i) Field wiring
(j) Power-supply cord
(k) Receptacles
(l) Spacing
(m) Operating mechanism
(n) Supervisory circuit
(o) Leakage current
(p) High-resistance ground fault
(q) Resistance to false tripping
(r) Regulation
(s) Normal temperature
(t) Dielectric withstand
(u) Overload and motor starting
(v) Low-resistance ground fault
(w) Endurance
(x) Abnormal operation
(y) Extra-low-resistance ground fault
(z) Short circuit

UL requires instructions for safe and effective use of GFCIs. Some of these instructions must appear on GFCIs and be readily viewable when the GFCIs are installed.

11.2. UL Field Investigations

UL investigated GFCIs by placing 100 units in various locations throughout the USA [24]. Two manufacturers supplied 50 units each. The test duration was eighteen months. During this investigation there were 46 incidents of automatic circuit interruption which appeared to be due to ground faults. The cause of the GFCI operation was determined for nearly all of these circuit interruptions. In addition there were 26 incidents of tripping believed to be associated with local electrical storm activity and ten other incidents which could not be associated with any specific cause.

11.3. GFCI Performance Tests

To assure that GFCIs will prevent electrocution, Dr. Archer S. Gordon, of Statham Instruments, Inc., Oxnard, California, administered 2400 shocks to dogs

under anesthesia [6]. Experiments that may produce ventricular fibrillation cannot be made on man, and the only alternative is to experiment on animals and try to relate the experimental data to man. See section 2.3.5.

Commercial 5 mA GFCIs were used. Dogs were connected electrically from the "hot" wire of the 120V laboratory circuit to ground. The dogs were given 800 shocks with a current pathway between right forepaw and left hind paw. This was to stimulate the frequently experienced arm-to-leg pathway in many human electrocutions. No incidence of ventricular fibrillation was observed. Eight hundred additional shocks were then given to the dogs after electrodes were placed on the right forepaw and left forepaw. None of these 800 shocks produced ventricular fibrillation. However, 36 fibrillations were produced during the course of 800 shocks applied with electrodes placed on opposite sides of the chest. This result is alleged to be not important from a safety viewpoint, since such a pathway is unlikely in human accidents. Moreover, since the minimum current for producing ventricular fibrillation in mammals is approximately proportional to body weight, the authority states that it is evident that the GFCI will protect human beings, including the very young [6].

11.4. Routine Tests

UL requires that the supervisory circuit (test button) circuit of a cord-connected GFCI be operated before an appliance is plugged into any receptacle protected by the GFCI. See section 4.2. UL also requires that the supervisory circuit of permanently connected GFCIs be operated upon installation and at least as frequently as monthly. UL requires that the user be informed that in the event of improper function of a GFCI when the supervisory circuit is operated, he is to correct the cause of the malfunction before further use of the device. [1]

12. Foreign Experience

The GFCI had wide applications in other parts of the world such as Germany, France, Australia and South Africa, prior to extensive use in the USA. [9] The primary problem in foreign experience was striking a proper balance between a trip value low enough to provide protection but high enough to prevent nuisance tripping because of leakage currents encountered in wire, appliances and other electrical equipment. The sum of all leakage currents on the load side of a GFCI will be sensed by the GFCI.

In South Africa, units rated at 5 mA had to be taken off the market due to nuisance tripping [9]. After a three-year investigation, the South African Bureau of Standards agreed to 20 mA as a safe trip value and satisfactory protection has been reported with GFCIs rated at 20 mA. In France good experience with 40,000 units with a 30 mA trip rating has been reported. [9].

13. Controversies Concerning the Use of GFCIs

In spite of research, testing and in-use experience, there is considerable controversy over the merits of GFCIs. Comments stating why GFCIs should be required in various locations, comments challenging their need, their reliability, and problems they create are contained in (1) the pre-print of Proposed Amendments to the 1974 National Electrical Code (NEC) [25] and (2) in public hearings held by the Occupational Safety and Health Administration in December, 1973 [26]. Some of these comments expressing various points of view are listed below. (The 1975 edition of the NEC [2] was originally scheduled to be the 1974 edition).

13.1. Arguments for the Use of GFCIs

". . . With the greatly increased use of electrical appliances in the home, especially in the kitchen, bathroom and garage areas, danger of personal injury through ground fault conditions have also increased. There is now more contact with various types of electrical equipment than ever before. Requirements of ground fault protection on potentially dangerous outlets can save hundreds of lives annually. Since the NEC has almost sole responsibility in safeguarding the consumer in this area, . . ." [25]

". . . The shock hazard associated with out-door receptacles exists regardless of location. More than half of the electrical accidents occur in other than residential occupancies. Many cord-connected appliances used in the home, hotels, motels and similar dwelling occupancies are of the two-conductor non-grounded type. These appliances become particularly hazardous when the user is grounded or exposed frequently to ground." [25]

". . . Hand-held appliances used in kitchens are normally not provided with a grounding conductor, and the user is exposed to possible shock hazard from the use of these appliances in association with water and grounded surfaces." [25]

". . . The bathroom is one of the most hazardous places in residential occupancies for people using electrical equipment, and since a receptacle is now required in bathrooms, protection equal to the protection required for personnel using out-door receptacles should be provided in bathrooms also." [25]

". . . The Corps of Engineers states, * * * this survey shows that 294 contractors performing various types of construction work are using ground-fault circuit protection. All units were reported to be operating to the satisfaction of the contractors' . . ." [26]

". . . A total of 52 fatal accidents which could have been prevented by the use of GFCIs on construction sites was found by studying all the data submitted.

This data covered the period from January 1970 to September 1974 . . ." [26]

13.2. Arguments Against the Use of GFCIs

". . . The Electrical Employers Self-Insurance Plan of New York City, which maintains accurate accident statistics for approximately 22 million manhours of construction work per year reports that they have had no accidents that would have been prevented by the use of the ground fault interrupter . . ." [25]

". . . The devices are still subject to unexplained trip-outs which result in shut-downs of production usually for more than one craft and probably eventual by-pass of the device." [25]

". . . It is my recollection that the Panel agreed that GFCIs are not practical on shore power receptacles because of leakage current inherent in boats . . ." [25]

". . . The present ground fault interrupters for personnel protection have sensitivity trip level of 5 mA. Due to the fact that some portable dishwashers and frost-free refrigerators contain calrod heating units which have leakage up to 100 mA when energized, it would be impractical to require ground fault interrupters where these are used. Additional research in the form of fact finding studies must be accomplished before requirements of this magnitude are made mandatory." [25]

". . . It is felt that further approval of ground-fault circuit protection should be withheld pending the establishment of some solid favorable evidence on the performance of ground-fault circuit protection presently being required for outdoor residential outlets under this section. It is noted that several of the Western European countries, with several years experience, have established a 20 mA trip position as being appropriate while our requirements are only 5 mA" [25].

". . . Some commenters expressed concern that many GFCIs tripped well under 5 mA (i.e., 2.5 mA or less) . . ." [26].

". . . Many commenters claimed that this standard would have a severe economic impact. Some commenters claimed it would cost hundreds of thousands of dollars for large companies to comply. They claimed that these costs would not be offset by any substantial gain in safety . . ." [26].

14. Summary

1. Ground fault circuit interrupters are designed to open electric circuits prior to the time a normal adult or child would receive energy sufficient for electrocution; a person would, however, ordinarily feel the shock.

2. There is increasing use of GFCIs in this country because of increasing requirements in Codes and other rules issued by enforcing authorities.

3. There was wide use of GFCIs in some foreign countries prior to their extensive use in the USA.

4. The effectiveness of GFCIs has been demonstrated by tests on dogs. (See section 11.3).

5. Principal controversies concerning GFCIs involve nuisance tripping, reliability over an extended period of time and the application of GFCIs to older buildings.

6. Because of leakage currents encountered in wire and other electrical equipment in various locations and applications, there are controversies concerning the feasibility of GFCIs.

7. A principal detriment to the feasibility of GFCIs appears to be the questionable reliability because of the frequent routine testing (monthly operation of the test button) which is required; such testing appears impractical to enforce in residential occupancies.

8. The rationale of requiring permanently installed GFCIs in new buildings, but largely ignoring older buildings needs to be examined.

9. The practical problems of leakage current appears to be the principal technical parameter which needs investigation for the use of GFCIs in older buildings.

15. Recommendations

1. Additional laboratory and field investigations involving nuisance tripping and reliability aspects of GFCIs should be performed.

2. The feasibility and need of GFCIs in various applications and in various locations needs investigation. The need for GFCI protection of branch circuit wiring should be evaluated by the Occupational Safety and Health Administration or the Consumer Product Safety Commission.

3. Leakage current data, particularly on wiring and other electrical equipment in older buildings, should be obtained.

4. The rationale of requiring the use of GFCIs in older buildings and appropriate methods to implement such requirements should be undertaken by an appropriate group such as that indicated in Recommendation 2 above.

5. Standards for GFCIs to be used on older installations should be developed after appropriate leakage current data has been obtained.

6. Work concerning the adaptation of GFCIs for use on circuits with flat conductor cable should be initiated.

7. Additional data on shock hazards particularly as it pertains to children, the elderly and infirm should be obtained as background information for GFCI technology.

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APPENDIX D

UL REPORT

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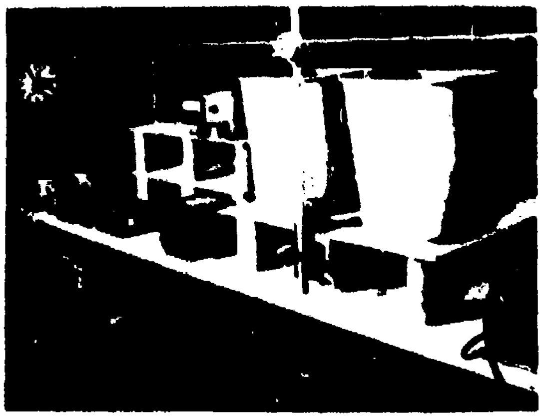


GENERAL VIEWS OF LABORATORY SET-UP FOR LEAKAGE CURRENT AND WATER RESISTIVITY MEASUREMENTS

LEAKAGE CURRENT MEASUREMENTS

NEW CORD

DATA SOURCE	CORD TYPE	LEAKAGE CURRENT PER 100 FEET OF CORD: CORD LYING ON GROUNDED CONCRETE SLAB	CORD LYING ON GROUNDED STEEL PLATE	CORD IMMERSED IN WATER*
Prof. Dalziel	SO	0.85 mA		
ULI	14/3 SO		0.59 mA	1.27 mA

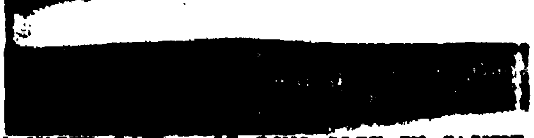
* 9,100 ohm-cm water at 47 deg. C

LEAKAGE CURRENT MEASUREMENTS

NEW CORD

CORD SIZE, NO. OF CONDUCTORS, TYPE & COLOR	LEAKAGE PER 100 FT IN AIR	LEAKAGE PER 100 FT. IN WATER: WATER RESISTIVITY	LEAKAGE
10/3/STO - YELLOW	0.115 mA	8500 OHM-CM 27 OHM-CM	0.425 mA 0.416 mA
10/3/STO - GRAY	0.128 mA	28 OHM-CM	0.425 mA
14/3/ST - GRAY	0.101 mA	29.5 OHM-CM	0.256 mA
14/3/S - BLACK	0.096 mA	29 OHM-CM	0.435 mA
16/3/S - BLACK	0.132 mA	2950 OHM-CM	0.344 mA

DAMAGED CORD - 1/4" X 3/8" PIECE REMOVED



DAMAGED CORD - 3" LONG SLIT IN JACKET

LEAKAGE CURRENT MEASUREMENTS

DAMAGED CORD

CORD TYPE 16/3 Type SO with paper and jute fillers

FORM OF DAMAGE (1) 3 inch long slit through jacket.
and (2) 1/4 inch by 3/8 inch piece of jacket removed

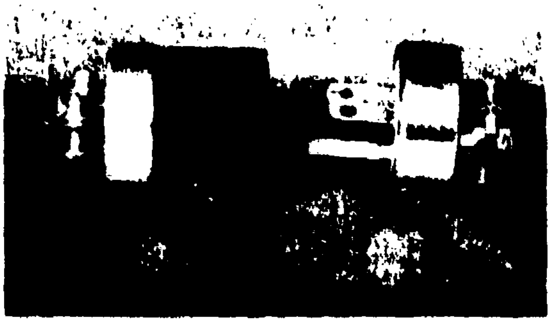
In both cases, the individual conductor insulation was undamaged

IMMERSION TIME 72 hours

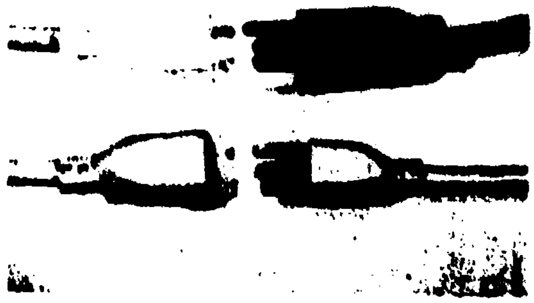
INCREASE IN LEAKAGE CURRENT OVER THE SAME CORD WHEN UNDAMAGED:

For a 100 foot length of cord - Less than 5%
For a 10 foot length of cord - Just under 75%

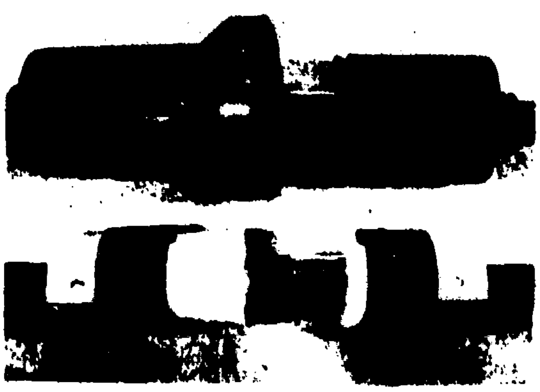
Phone 516 271 6200 Telex. 96-1456 Cable UNDLAB MELVILLE



ARMORED TYPE
PLUG & CONNECTOR

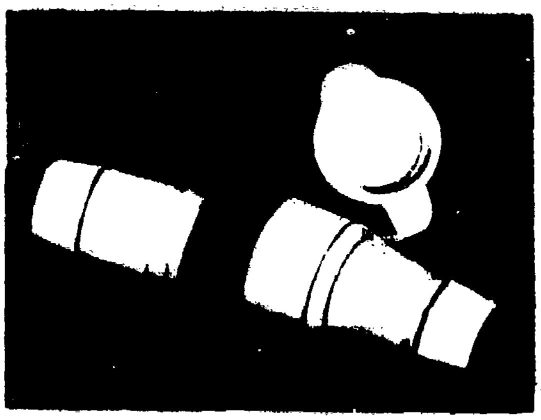


MOLDED-ON TYPE
PLUGS & CONNECTORS



ALL INSULATED TYPE
PLUG & CONNECTOR

WITH AND WITHOUT
PROTECTING BOOTS



PLUG & CONNECTOR
WITH INTEGRAL SEAL

LEAKAGE CURRENT MEASUREMENTS

CAPS AND CONNECTORS

TYPE OF CONNECTOR & CAP	HOW JOINED	WATER RESISTIVITY OHM-CM	LEAKAGE CURRENT
MOLDED-ON	FACES IN CONTACT	2950 295*	1.9 mA 6.0 mA
	1/32 INCH GAP BETWEEN FACES	2950 295*	10.3 mA 130 mA
ALL-INSULATED (NO ARMOR)	FACES IN CONTACT	3200 295*	**21.0 mA 310 mA
ARMORED	FACES IN CONTACT	3200	51.0 mA

*TYPICAL OF WATER CONTAMINATED WITH PORTLAND CEMENT

**WHEN REMOVED FROM THE WATER AND SHAKEN TO DISLODGE THE WATER DROPLETS, THE LEAKAGE CURRENT FROM THE REASSEMBLED COMBINATION WAS 6.1 mA

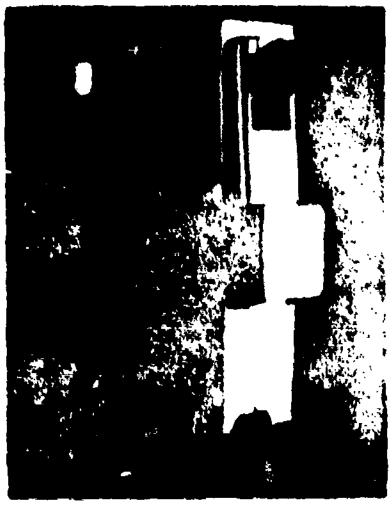
LEAKAGE CURRENT MEASUREMENTS

INSULATING BOOTS

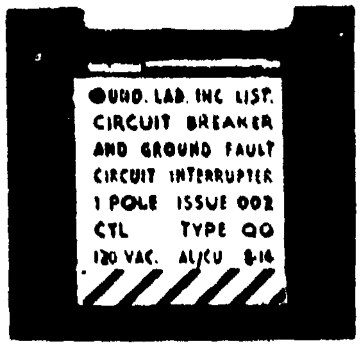
&

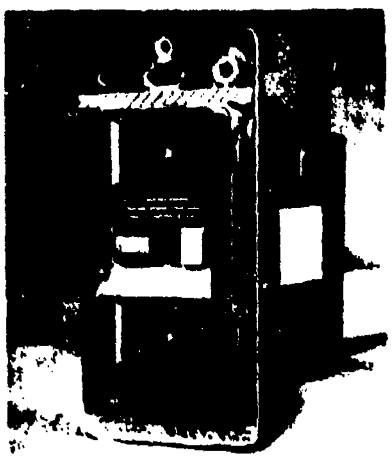
SEALED CONNECTOR

TYPE	IMMERSION TIME	WATER RESISTIVITY	LEAKAGE CURRENT
Boots over all-insulated cap & connector	42 hr	3000 ohm-cm	0.021 mA max
Integrally sealing cap & connector	48 hr	300 ohm-cm	0.085 mA max

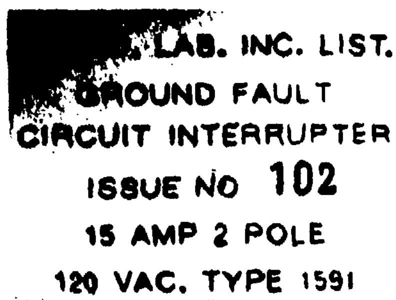


A COMBINATION CIRCUIT BREAKER AND GROUND FAULT CIRCUIT INTERRUPTER





A GROUND FAULT CIRCUIT INTERRUPTER IN COMBINATION WITH A DUPLEX RECEPTACLE



APPENDIX E

SUMMARY OF FIELD DATA
(Developed from Discussions with Corps of Engineers and Contractor Personnel at Field Sites)

CONTRACTOR	SITE NAME LOCATION	NUISANCE TRIPS POSSIBLY CAUSED BY MOISTURE	RFI	DEFECTIVE GFCI	EXTENSION CORDS	COMMENTS
Not identified	Ft Hunter Savannah, GA	No	No	Not reported	Long extension cord	One incident of tripping caused by dampness of electrical conductor cleared up when conductor was water-proofed. Condition of electrical cords is policed closely. A good education program existed here.
Harry Eckstein Corp.	New Melones Dam and Lake Jamestown, CA	Yes	Yes	Not reported	Long extension cord	Hazard created by throwing workers and traffic in total darkness.
Valley Inland Pacific Co.	Lost Creek Dam Medford, OR	Yes	No	Not reported	Long extension cord	Extension cord had waterproof plugs and receptacles.
Not identified	Portland Dist.	Yes	No	Low threshold currents	Long extension cord	Conversation with Chief of Construction and Chief of Safety office. No site was visited.
Sellere, Agsher Titan Mt States Co.	Ft Lewis Tacoma, WA	No GFCIs were in use here				Electrical circuits for contract work were pulled from existing wiring in building. Interpretation of requirement was found to vary from District to District.
Not identified	Vicksburg, MS	Yes	Yes	GFCI failed shortly after installation. Low threshold currents	Long extension cord	Installing breaker GFCI in existing circuits of old wiring caused problems. Transients induced by radial arm saw caused trips.
Not identified	Corps of Engineers Field Office, Lafayette, LA	No	Yes	GFCI functioned properly when replaced	No long extension cords reported here	District required GFCI on all trailer circuits and cal-rod type electrical baseboard heater would trip the GFCI. A defective CB radio base also tripped the GFCI. Dredges required to install GFCI would not work with existing wire.
Jones and Teers Co.	Smithland Lock and Dam, Smithland, KY	GFCIs were being installed but not in use				Contractors indicated that their experience showed trip values too low for practical use on construction sites. They requested permission to use GFCIs with higher trip values.

CONTRACTOR	SITE NAME LOCATION	NUISANCE TRIPS POSSIBLY CAUSED BY MOISTURE	RFI	DEFECTIVE GFCI	EXTENSION CORDS	COMMENTS
Wolf and Trans Elect Co	Ft Campbell, KY	Yes	No	High rate of GFCIs (25 percent)	Long extension cord	Initial and periodic checking eliminated all defective GFCIs.
Not identified	Fort Carson and Peterson Field, CO	Yes	No	Problems in resetting	Long length reportedly causing problems	Initial opposition to requirement, but apparently well accepted now.
Hensel Phillips Co.	Lowry AFB Denver, CO	Yes	No	Life span about 4 weeks	Extension cords in poor condition	Corps field personnel were convinced that problems were caused by poor extension cords.
Not identified	Walter Reed Hosp Wash, DC	No	No	Not reported	No problem reported	Reported that dropping cords in water and mud or running over or cutting cords caused tripping.
Beck	Anchorage and Shemya, AL	Yes	No	Not reported	Long length reportedly caused nuisance trips	A GFCI used on a portable distribution box had been jumped to eliminate nuisance trips. This was the only GFCI at the site. Conversation with the Anchorage Division indicated a good GFCI inspection and educational program.

APPENDIX F*

SUMMARY OF COE FIELD STUDY

1. At the request of DAEN-SO, COE field offices monitored GFCI use and experience on all current civil works and military construction projects within continental United States from 19 April through 21 May 1976. The following is a compendium of the findings:

a. 884 Corps Construction Contracts required ground fault circuit interrupters (GFCIs) for the protection of personnel on construction sites.

b. 4038 GFCI approved Class A devices were being used (709 portable, 1459 receptacle, 1654 branch circuit breakers, and 261 load centers).

c. 4821 trips of GFCI devices were reported. This is an average of 0.236 trips per device per week--or about one trip per month, which is not considered excessive. Analysis of trip causes indicated that nuisance trips were minimal and not a problem in the field. ("Nuisance trip" was defined as an uncorrectable trip from an unknown source, such as lightning, radio noise or an unusual combination of circumstances.) On 368 contracts, fewer than three trips of GFCI devices during the 5-week period were reported.

d. The 4 to 6 mA trip level for GFCI Class A devices was operating effectively and properly as indicated by inexcessive tripping. Thus, this level was adequate for construction sites.

e. Electrical safety has improved significantly through attention brought about by enforcement of GFCI protection. Some of the more important safety factors reported were:

(1) One contractor employee was saved from electrocution.

(2) Better quality and safer extension cords resulted from replacement of inferior or faulty cords which caused tripping of GFCI devices.

(3) Hazardous and unsafe portable tools and equipment such as drills, saws, grinders, concrete vibrators, and submersible pumps which caused tripping of GFCI devices were replaced.

(4) Improved bonding and grounding systems resulted from replacement of defective receptacles, cords, and connections that caused tripping or no protection of GFCI devices. Note: Reliable ground systems cannot always be assured on construction sites. Enforcement of GFCI protection led to a more reliable grounding system.

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*Developed from data submitted to OCE covering all GFCI tripping at construction sites during the period 19 April through 21 May 1976. The summary is included as additional information; it was not considered in arriving at the recommendations of this report.

(5) Use of GFCIs has called attention to overloaded circuit conditions. GFCIs were blamed at first, but a check of the circuit breaker and loads revealed that additional circuits were needed. Overloading of circuits can occur even without GFCIs, but GFCIs provided better and quicker indication.

f. Enforcement has been no major problem.

(1) Only two waivers were granted, both at one project site, and both for limited contract areas. The two waivers represent 99.8 percent enforcement and an excellent safety record when AGC members were aware of Corps policy to grant waivers.

(2) Six Districts enforced grounding of all generators as required by Corps Safety Manual EM-385-1-1. Although this exceeds the NEC requirements, no problems resulted.

(3) Allowing the use of permanent building wiring in lieu of GFCIs was based on the determination of the Contracting Officer. In general, we encouraged going to permanent building wiring as soon as possible to utilize a more reliable grounding system. This was not considered as a waiver since this exception is allowed by the NEC. Permanent building wiring was being used wherever possible and assisted in making enforcement a cooperative arrangement.

2. Recommendations:

a. Continue the use of approved GFCI devices on construction sites for protection of personnel.

b. Trip level of 4 to 6 mA is adequate for construction sites.

c. Encourage the use of GFCI devices on other projects in order to obtain easier enforcement, standardization, and improved electrical safety.

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